AD607619

A SURVEY OF HIGH TEMPERATURE
CERAMIC MATERIALS FOR RADOMES

FOREWORD

This report was prepared by Melpar, Inc., Falls Church, Virginia, under Air Force Contract No. AF33(657)-10519. The contract was initiated under Project No. 7381, Materials Application Task No. 738105, Ceramics and Graphite Technical Evaluation. The work was administered under the direction of the Air Force Materials Laboratory, Research and Technology Division with Mr. Lawrence Kopell acting as project Engineer.

This report covers the work conducted from 1 May 1963 to 1 May 1964.

During the course of this contract Melpar received excellent cooperation from all agencies, missile contractors and material suppliers associated with the development of nonmetallic inorganic refractory materials for use as elevated temperature radomes. It would be almost impossible to give proper credit to all those individuals in both private industry and the Air Force who contributed to this program. Special mention is made, however, to the contribution of the Navy Department in providing a detailed knowledge of the various programs under its sponsorship.

Melpar wishes also to acknowledge the contributions of Dr. Chen Tai, Ohio State University, and Richard D'Amato, Electronics Space Structive Corporation, Concord, Massachusetts, who served in the capacity of Consultants for this effort in the fields of electro-mechanical design and structural analysis, respectively.

ABSTRACT

A comprehensive survey was conducted of available information concerning the use of nonmetallic inorganic refractory material in the fabrication of radomes for elevated temperature use. In conducting this survey, both open literature and contract reports were studied. These were augmented with facility visits and personal communications with both missile contractors and materials suppliers.

The comments of other Government agencies were actively solicited to insure all active contract efforts in this field of research would be included in this report. In addition, views concerning future efforts in the fabrication of radomes from nonmetallic inorganic refractory materials were also discussed in an effort to determine the direction of advanced planning in this area of research.

The available data were analyzed to determine their validity, and that information considered to be reliable and accurate was compiled in both tabular and graphical form.

Throughout this effort, it was difficult to characterize completely the majority of the materials in terms of chemical composition.

This technical documentary report has been reviewed and is approved.

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1. INTRODUCTION

The use of radomes to protect the guidance systems of both aircraft and missiles has been a standard practice since the advent of airborne radar during World War II. Throughout the last decade, the aerospace industry has strived to achieve ever increasing requirements of range, speed, and maneuverability. The mission of each successive generation of missiles then results in higher Mach numbers, and trajectories that include either a much steeper angle of attack or prolonged periods of time during re-entry into the earth's atmosphere. In each case, the vehicle experiences a more extreme thermal environment. As a consequence, all phases of missile technology have found it necessary to utilize materials with high temperature capabilities in construction.

The accuracy of navigation, or guidance, becomes increasingly important as the range and speed of propulsion of a vehicle are increased. Even minute errors in the trajectory of a long-range vehicle can result in gross deviation from the planned destination. Similarly, as the time of transit is reduced, so is the allowable time for corrective measure in the trajectory to bring a missile back onto its planned course.

The operational characteristics of a number of the current and developmental missiles are such that the all-important guidance radar can no longer be adequately protected by high temperature plastics. As a consequence, use has been made of nonmetallic inorganic refractory materials in the construction of the radomes. The importance of the radome in the total missile effort cannot be overlooked. Without radomes capable of providing satisfactory performance, both structurally and electrically, the advanced missile program will be severely restricted.

In September of 1957, the Electronic Components Laboratory of Wright Air Development Center published WADC Technical Report Number 57-67, "Techniques for Airborne Radome Design." This document was published during the time when industry was realizing an ever increasing need for new and improved radomes. The urgency of the need was such that many technical personnel were entering the field of radome design and fabrication, and it was felt important to provide a design handbook that would familiarize them with all aspects of this critical area of endeavor. The primary emphasis of this handbook was upon the electrical design, with a more limited consideration of the materials used, and methods of fabrication. The majority of this information was, of course, with respect to plastics and laminates. At the present time, the McGraw Hill Book Company, Inc., is in the final stages of a contract

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effort for the AF Avionics Laboratory of the Research and Technology Division of Wright-Patterson Air Force Base to update this handbook. This will be issued as a supplement to the existing handbook, and will include the developments of the last seven years, so that those scientists and engineers only recently entering the field of radome design and production may have the benefit of current advances in theory and materials application.

Since the late 1950's, the missile radome industry has centered around the development of radomes from the nonmetallic inorganic refractory materials necessary to satisfy the thermal performance of many current and most future missiles. Throughout this period, technical discussions have concerned themselves with the application, and all technical personnel are well aware of the fact that this type of a radome is used. It is interesting to note that, in spite of the degree of interest and the earnest need for radomes manufactured from these materials, there is an amazing lack of readily available detailed technical information concerning material properties, fabrication techniques, or problems associated with the application to this use.

1.1 Purpose

The purpose of this report is to survey the literature and previous contract reports and to compile the available data concerning the use of nonmetallic inorganic refractory materials utilized for elevated temperature radomes. This study was not conducted to establish actual design criteria in the sense of a detailed consideration of either electro-magnetic design theory or specific fabrication processes. Rather, the objective was to present the available information concerning these materials and their properties, in order that it would be possible to ascertain the state of the art in the use of nonmetallic inorganic refractory materials in the fabrication of radomes, relative to the need and advance of the overall radome technology.

The satisfactory performance of this class of material is dependent upon more than merely dielectric properties. Consideration must also be given to mechanical strength and thermal characteristics. The total design for any mission is a function of a complex relationship between all these parameters. This is further complicated by the relationship that each individual property has to the thermal environment. To solve this problem, representative thermal and mechanical property data for each material were also compiled, but no attempt was made to conduct a comprehensive survey concerning these properties. An extremely large amount of information has been published concerning the mechanical properties of nonmetallic inorganic materials over the years, and to attempt to include this as a major portion of this program would not have been possible. In order to include some representative information, Melpar was directed to utilize the results of two other Air Force contracts specifically dealing with these properties. These are AF 33(657)-8326, conducted by Battelle Memorial Institute to study information on the thermal and mechanical properties of brittle materials, and AF 33(657)-8064, conducted by the Ohio State University, which is concerned with a survey of the mechanical properties of brittle materials.

1.2 Current Use of Nonmetallic Inorganic Refractory Radomes

Table 1 shows a list of current missile systems that carry radomes. In each case, the material used to fabricate the radome and its size are presented. The prime contractor is identified, as is the subcontractor making the radome. In order that one may place the use of nonmetallic inorganic refractory materials in proper perspective relative to the use of organic materials and laminates, the missiles are also listed.

Corning Glass Works is the sole supplier of Pyroceram, which is a proprietary material. Pyroceram has gained in popularity as a consequence of sled tests which showed that this material exhibited superior performance to aluminum oxide materials. Proprietary considerations prevent Corning from making Pyroceram manufacturing processes and chemical composition public information.

Coors Porcelain Company and the Western Gold and Platinum Company manufacture radomes from aluminum oxide. Both firms manufacture radomes from their standard line of aluminum oxide materials, rather than attempt to develop a special body for this purpose.

Western Gold and Platinum Company uses their standard AL300 body, a 97.6% Al_2O_3 composition. The standard production process used for all types of manufacturing is used. The only step in production that differs from any other production run is the particular material that is used as the master. These are all the property of the individual customer. All of the radomes are isostatically pressed at pressures of 8000 to 10,000 psi.

Currently, two types of radomes for the Sparrow missile are produced. If only a blank is desired, the Al_2O_3, mixed with its binder, is loaded into a mold that has only an internal mandrel, and the typical loose-fitting rubber bag around it. After pressing, the part is machined to approximate size in the semi-fired state, and then fired to maturity. If a radome is to be pressed with a prescription in it, a different mold is used. This consists of a male mandrel with a cast iron shroud on the outside of the rubber bag. When this mold is loaded, closer control of the overall dimension can be achieved; a pressure of 8,000 to 10,000 psi is used in the isostatic pressing. The Western Gold and Platinum Company is able to maintain a variation of density throughout a finished radome of $\pm 1\%$. It should be noted that the fabrication of prescription radomes is an experimental program only.

Coors Porcelain Company also uses isostatic pressing as the means of radome fabrication and the materials used are standard production bodies. The pressure used in molding is 6000 psi. Coors offers a wider range of composition, with four bodies considered to be suitable for radome application. These are grades AD94, AD96, AD99, and AD995. In all cases, the number designation indicates the percentage of Al_2O_3. These bodies range from 94% to 99.5%, respectively. Coors Porcelain Company does not attempt to press a radome with a prescription determined by the mandrel. Rather, this company makes extensive use of an elaborate grinding facility to achieve the final dimensions on the radomes it fabricates.

TABLE 1
RADOMES USED IN CURRENT MISSILE PROGRAM

	MANUFACTURER	DOME MATERIAL	DOME CONFIGURATION	DOME DIMENSIONS Length	Base Diameter	MISSILE	SERVICE	CONTRACTOR
1	Brunswick Company	Plastic Filament wound Vibrin 135	Ogive	8 Ft.	2 Ft.	Bomarc (Cancelled)	Air Force	Boeing, Seattle, Wash.
2	Brunswick Company	Plastic Laminate	Ogive	18 In.	8 In.	Corvus (Failure)	Navy	Tempco Texas
3	Brunswick Company	Plastic Filament wound	Ogive	16 In.	8 In.	Shrike (AGM-45)	Navy	NOTS, China Lake, Calif.
4	Brunswick Company	Plastic Filament wound PC 2106 Quartz fab Silicone (DC 2106) resin	Ogive	38 In.	14 In.	Eagle (Failure)	Navy	Bendix Res. Labs Detroit, Mich.
5	Corning Glassworks	Pyroceram	Hemisphere		6 In.	Gar XI	Air Force	Hughes Aircraft Culver City, Calif
6	Corning Glassworks	Pyroceram	Ogive (mod)	42 In.	14 In.	Phoenix (TFX missile)	Navy	Hughes Aircraft
7	Corning Glassworks	Pyroceram	Ogive	16 In.	8 In.	Shrike	Navy	NOTS
8	Corning Glassworks	Pyroceram	Ogive	37 In.	12 In.	Tartar	Navy	General Dynamics
9	Corning Glassworks	Pyroceram	Ogive	37 In.	12 In.	Terrier	Navy	General Dynamics
10	Corning Glassworks	Pyroceram or Silica	Ogive(?)			Typhon (Cancelled)	Navy	Johns Hopkins A.P.L.
11	Corning or Coors	Pyroceram or 99% Al_2O_3	Von Karmen	36 In.	14 In.	Gar IX	Air Force	Hughes Aircraft
12	Corning (changed from Coors after Sled test)	Pyroceram	Ogive	37 In. (Approximate)	14 In.	Genie (thin-walled) (cancelled)	Air Force	Douglas Aircraft Santa Monica California
13	Corning or Coors under consideration	Pyroceram or 99% Al_2O_3	Hemisphere		6 In.	Sera (elec. head other-wise same as Sidewinder)	Navy	NOTS, China Lake, Calif.
14	Interpace (makes ovrsz blanks)	97.6% Al_2O_3	Ogive	18 In.	8 In.	Sparrow III	Navy	Raytheon, Bedford, Mass.
15	Wesgo (Western Gold and Plat)	97.6% Al_2O_3	Ogive	18 In.	8 In.	Sparrow III	Navy	(Raytheon in Bristol, Tenn. grinds oversized blanks to size)
16	Raytheon	Plastic (seamless fiberglas sock)	Ogive	37 In.	12 In.	Hawk	Army	Raytheon
17	American Lava	Al_2O_3	Hemisphere		6 In.	Sidewinder (Infra-Red Head)	Navy and Air Force	NOTS, China Lake, California
18	....	Fused Silica	Ogive(?)	....	2 In.	Red Eye	Army	General Dynamics
19	Zenith Plastics (considering changeover to Pyroceram by Corning)	Diayll 128	Ogive	13 In.	5 In.	*Mauler	Army	General Dynamics
20	Navy					Walleye (TV guided)	Navy	NOTS, China Lake, Calif.
21	Navy					Regulus (all inertial but has radome)	Navy	Ling-Tempco-Vought

*Note - All sled tests are conducted to Mauler Specifications

The International Pipe and Ceramic Company and the Shenango Ceramics Company have taken different approaches to the manufacture of radomes from aluminum oxide. Instead of using a standard production body, both have development compositions specifically for radome application that best suit their individual processes.

The International Pipe and Ceramic Company uses a process that consists of spraying a slurry of Al_2O_3, made using an organic solvent rather than water, onto a radome mandrel. Once a sufficient thickness has been built up, the mandrel with the coating of Al_2O_3 is placed in a rubber bag, and the radome is then isostatically pressed at 35,000 psi. After removal from the mandrel, the radome is fired at 2400°F. It is then machined to the desired blank size on the outside only, and fired to maturity at 3150°F. These blanks are then supplied to the user for final prescription machining. This body is a 97.4% Al_2O_3 formulation. The staff of the International Pipe and Ceramic Company feel that a 99% Al_2O_3 radome could be fabricated by the same process.

The Shenango Ceramics Company has developed a slip-casting technique to fabricate aluminum oxide radomes. This process is basically one of carefully centering of male mandrel ground to the desired prescription within a female cavity. The Al_2O_3 slip, in a fluid state is then forced into the mold under a rather low pressure. Once the water has been drawn out of the cast radome, it is released and dried. After complete drying has been accomplished, the radome is then fired to maturity. The nature of the slip-casting process does not favor the use of a high-purity aluminum oxide composition, and the resulting radome is of the order of 84% Al_2O_3. While this is quite low compared to the compositions prepared by other manufacturers, indications are that it is satisfactory for a number of applications. The staff of the Shenango Ceramics Company is of the opinion that the shrinkage and distortion of their body can be controlled sufficiently well to permit eventual fabrication of radomes by the slip-casting technique that will require no additional machining. To date, the Shenango Ceramics Company has made only experimental radomes.

1.3 Chronological Sequence of Radome Development Using Nonmetallic Inorganic Refractory Materials

The use of nonmetallic inorganic refractory materials to fabricate radomes was originally discussed as early as the middle 1940's. The first attempts to form such structures did not occur until the middle 1950's. The development since that time has included a number of actual production contracts, as well as purely fabrication development feasibility studies. In addition, there have been numerous orders placed with material suppliers for one or two radomes of a kind to be evaluated for use in prototype missile systems. At the same time, Government agencies have sponsored a number of materials research programs that have been more or less closely related to radome development technology.

The following discussion of these programs is divided into four parts: aluminum oxide, Pyroceram, fused silica, and materials development.

It is not feasible to cover every contract and subcontract awarded during this period of time. In a number of instances, the work was conducted on a straight purchase order basis, and no reports were involved. In the case of many major prime contracts, the reports of the manufacturer were filed as a portion of the contract records and never received dissemination beyond this point.

By the same token, the discussion of materials research effort is also in the vein of a commentary. This is done to provide a discussion of typical programs, and to place them in an approximate time relationship to the total radome effort over the last eight or nine years.

1.3.1 Aluminum Oxide As a Radome Material

The Coors Procelain Company and the International Pipe and Ceramic Company (Interpace) entered into the fabrication of aluminum oxide radomes about the same time -- late 1955 to early 1956. At that time Interpace was known as the Gladding McBean Company.

Coors Porcelain began its development of a process for forming radome shapes under contract to the W. L. Maximum Corporation of New York. This effort was concerned with the development of a radome program for the Corvus Missile, which was terminated before any production radomes were ordered.

Interpace entered into the field of radome fabrication by means of a feasibility study awarded from AMC for the development of a monofilament aluminum oxide radome. This program was associated with the Falcon missile system which never became operational.

In 1958, Coors Porcelain Co., Interpace, and the Norton Company all accepted contracts from AMC as a portion of a development effort for large ceramic radomes intended for end use on the Bomarc Missile system. This total radome effort was of an extremely broad nature, such that a number of additional subcontracts were involved. The final report, published as ASD TDR-62- 67 was not issued until early in 1962. In conjunction with the actual fabrication of experimental radomes, Melpar, Inc., conducted a subcontract to evaluate all of the physical, electrical, and thermal properties of the bodies used by each manufacturer to fabricate these radomes; General Applied Science Laboratories, Inc., conducted a theoretical and experimental study of the thermal shock characteristics of radomes produced by Coors Porcelain Company; and the Boeing Aircraft Company conducted a contract to study the attachment problem and material evaluation.

While the effort promised to provide the industry with important techniques in both manufacturing and materials development, the fact that no official documents were disseminated until all contracts of the effort were completed seriously reduced the overall usefulness of the program. Fortunately, the contractors involved in this effort were able to apply the individual knowledge that was gained in their portions of this effort to

other active missile system efforts. Since completion of this portion of the program, Coors Porcelain Company has not conducted any production contracts for large radomes of the Bomarc Size. Numerous production orders have been filled, however, for the Sidewinder Missile system.

In 1958, Interpace entered into a brief development contract for the Raytheon Corporation to provide a radome blank for the Sparrow III missile system. This was followed immediately by production orders which are still in progress today.

The Raytheon Corporation made the decision to use aluminum oxide radome on the Sparrow III program in about 1956. As indicated, Interpace was contracted to develop a prototype radome, which was then pressed into almost immediate production. The decision to use a nonmetallic inorganic refractory material in place of the organic radomes used in previous generations was based upon the advantages offered by a material with higher temperature characteristics.

The early electrical evaluation of aluminum oxide radomes showed satisfactory electrical performance under boresight evaluation; the experimental radomes that were flown were also satisfactory. Since using these radomes in production, Raytheon has no record of any instance of missile failure that can be attributed to the radomes.

In 1959, the Navy awarded a contract to the Shenango Ceramics Company to investigate the feasibility of fabricating aluminum oxide radomes by slip-casting techniques. This effort was completed in 1961 with the delivery of several experimental radomes. Subsequent electrical evaluation of these indicated that radomes produced by this technique could provide satisfactory electrical performance. This effort was followed, in 1962, by a subcontract from the Raytheon Corporation to investigate the feasibility of producing an aluminum oxide radome by the slip-casting technique that would provide usable electrical characteristics without the requirement for additional grinding after forming. Although progress was made toward this end, this contract was terminated in 1963, and no further pursuit of this technique is anticipated. In 1960, the Raytheon Corporation issued a contract to the Western Gold and Platinum Corporation for the production of aluminum oxide radomes -- blanks for the Sparrow III program. This order was filled and Western Gold and Platinum has been one of the two suppliers of these blanks since that date.

For the Sparrow missile, the Raytheon Corporation typically procures radomes as aluminum oxide blanks. These are then ground to the final electrical prescription at their Bristol, Tennessee, plant for use as operational radomes for delivery with each vehicle.

Throughout the last five to seven years, the Coors Porcelain Company, Interpace, and Western Gold and Platinum Company have filled numerous orders for prototype radomes and radome blanks in conjunction with many missile systems. In many of these instances, the systems were cancelled before the

radome was ever evaluated. In some cases, enough evaluation efforts were completed to demonstrate that the radomes would perform satisfactorily. This is the case in the development of the Genie by Douglas Aircraft Company. Several aluminum oxide radomes were fabricated, and each provided satisfactory performance in actual flights of this system. Table I provides an idea of the number of types of aluminum oxide radomes that have been fabricated as prototypes and production items.

In 1957, the industry in general was quite interested in the development of lightweight foamed aluminum oxide materials. These showed promise as broadband materials by virtue of their lower dielectric constants. During the years that followed, consideration was given to the fabrication of a sandwich radome, in which a layer of thin foam would be placed between two dense skins of aluminum oxide. The first study contract for this was awarded by the Navy in 1959. This is mentioned at this point to allow one to fit this development into the overall use of aluminum oxide, but detailed discussion of these efforts will be presented in one of the sections that follow. In 1963, AMC awarded a contract for the fabrication of a large aluminum oxide radome using mosaic techniques. This will also be discussed in a following section of this report.

1.3.2 Pyroceram

The Navy funded the Corning Glassworks for the development of the technique for fabricating radomes from Pyroceram during 1954. By 1955 and 1956, the process was well enough established that satisfactory radome blanks could be fabricated from this material. This development program was associated with the Terrier missile program and, during 1956, the General Dynamics Corporation procured the first prototype radomes for this missile. Since that time, General Dynamics has continued to use radomes fabricated from Pyroceram in production quantities. Both the Tarter and Terrier missile systems are designed around radomes fabricated from Pyroceram.

During 1956, Hughes Aircraft also began an initial consideration of radomes fabricated from Pyroceram for the Gar IX missile system. In 1958 Hughes Aircraft awarded a contract to Melpar, Inc. to determine the electrical, thermal and mechanical properties of Pyroceram at temperatures to 2250°F. This information was used to finalize the design criteria.

Since that time, Hughes Aircraft has used Pyroceram radomes on both the Gar IX and Gar XI missile systems and is presently intending to use Pyroceram on the Phoenix missile system. Pyroceram radomes have been selected for numerous other missile systems during this same period. In many instances, these radomes have been flown in preliminary tests and have demonstrated satisfactory performance.

1.3.3 Fused Silica

The Georgia Institute of Technology has been under contract to the Navy since 1955 in studies associated with radome development. Before 1958,

the studies were concerned with the thermal protection system, ablation rates, and investigations of material properties of the leading candidate material for radome use.

During 1958 and 1959, the first efforts toward actual radome development using fused silica were initiated. An aluminum model of a radome was fabricated and a number of radomes were cast of fused silica.

About this same time, ABMA at Huntsville became interested in the use of fused silica and a two-year effort was sponsored that resulted in a two-foot-high nose cone having a nineteen-inch base diameter. This fused silica nose cone was of a conical shape, not reinforced. This was not made with an intention of use for radar transmission, but rather as a thermal protection system for re-entry. Tests at the Huntsville re-entry facility indicated satisfactory performance.

Since 1960, the Georgia Institute of Technology has continued its investigation of fused silica radomes. Many of these have been supplied to NOTS for rain erosion sled tests.

During the development effort of the last 5 years, fused silica has shown considerable promise as a radome for elevated temperature use. The two most important factors in support of this application are its resistance to rain erosion and the ability to survive thermal shock. It should be mentioned that the rain erosion resistance has not been completely defined, and that additional efforts are currently being made to investigate more fully the use of a glaze to assist performance in this environment.

In 1961, General Dynamics became interested in fused silica as material for the fabrication of elevated temperature radomes; The Brunswick Corporation developed a similar interest in 1963, and presently both companies are supporting internal development programs to this end.

In 1963, The Air Force awarded a contract to the Georgia Institute of Technology for a radome in conjunction with the Trailblazer missile. This will be discussed in more detail in section 1.4.3 of this report.

1.3.4 Materials Development

Since 1955, both the Air Force and Navy have sponsored a number of projects concerning the development or investigation of nonmetallic inorganic refractory materials that have been associated with potential radome application. Typical of these are two long-term programs that have been funded continuously throughout this entire period. The Air Force has sponsored a continuing effort at the Massachusetts Institute of Technology associated with the precise determination of the dielectric characteristics of materials as a function of temperature. Much of their data is referenced in this report. During the same period, the Navy has funded work at Rutgers University. Prior to 1961, these efforts were directed specifically toward

radome materials for application on the Sparrow missile system. Since 1961, the objective of the program has been to develop improved nonmetallic inorganic refractory bodies with very uniform electrical and mechanical properties. It is hoped that this can be achieved through control of the processing technique.

Since 1959, the Navy has sponsored work at several agencies, including NOL, Vitro Laboratories, and the Brunswick Corporation, to study the method of coating plastics with nonmetallic inorganic refractory materials to resist rain erosion. While most of these efforts were specifically intended for aircraft, some benefit may eventually be realized in missile radomes.

From 1959 to 1961, The Air Force sponsored a program entitled "Research and Development Services Leading to the Control of Electrical Properties of Materials for High Temperature Radomes." This project dealt with a detailed study of the effects on the properties of aluminum oxide upon additions of impurities. Some of the results of this program will be discussed in more detail in the following section of this report.

In 1960, the Navy funded a program at the National Beryllia Corporation to investigate the application of beryllium oxide to aircraft radomes. This project is still in progress.

In 1961, the Air Force funded Horizons Inc., for a research effort associated with the development of a filamentized composite structure made from alumina oxide fibers. This effort has continued in 1962, 1963, and 1964 with emphasis upon the fabrication of large radomes.

In 1963, the Navy funded Melpar, Inc., for a study of the dielectric anisotropy of polycrystalline nonmetallic inorganic refractory materials. This study was an outgrowth of the fact that this phenomenon has been observed in many oxide bodies. In addition, early studies showed an apparent relationship between compressive stresses and dielectric constant. This program was initiated to study these relationships with respect to aluminum oxide to determine whether or not it is of consequence to radome design. This study is still in progress.

At present, the Air Force has a contract with Emerson and Cuming to determine the feasibility of fabricating a large sectionalized structurally supported airborne radome from nonmetallic inorganic refractory materials. A metal frame work is used to support the dielectric windows.

The Navy Department intends to fund a program at NOL to investigate thermal shock and other mechanical properties of a large number of nonmetallic inorganic refractory materials. In addition, a program to determine the relationship of microstructure to strengths at temperature was funded at ANCO Research and Development in 1962. This program is also still in progress. The Navy Department also funded, in 1964, a program at Linder Laboratories to investigate chemical strengths of material such as Corning Chemcor.

During 1964, the Hughes Aircraft company intends to initate a program to study the thermal shock characteristics of radomes fabricated from Al_2O_3, Pyroceram, and sandwich construction Al_2O_3 foam interlay constructions. These tasks will be general in nature, rather than associated with any one missile requirement. This should be of interest to all agencies and materials suppliers.

1.4 Current Materials Development

The preceding section of this report has outlined the manner in which radomes fabricated from nonmetallic inorganic refractory material have been accepted for operational use. The review of the historical development has been presented to provide an understanding of not only where industrial application of these materials is today, but just how it arrived at this point. In normal engineering application, the materials development is usually tied closely with a product or, more frequently, it precedes it in time. The evidence presented in this report indicates that this is not the case in the application of nonmetallic inorganic refractory materials to radome use. This portion of the report is devoted to current materials development.

1.4.1 General Lack of Materials Development

The term "materials development" in the context of this report is considered to mean those efforts specifically devoted to the improvement of any or all basic properties and characteristics of either a specific material or broad category of materials. This distinction is important, for it is an established fact that each of the missile efforts listed in Table 1 have had development tasks associated with the use of nonmetallic inorganic materials to fabricate radomes. In addition to these, the Air Force and Navy have both sponsored independent programs of a similar nature.

The fact that the major materials manufacturers had little experience in the fabrication of large shapes from these materials dictated the sense of direction in these programs. This was, of course, further complicated by a need for precise control of physical dimensions using a material that behaves differently than those previously used for this application. As a consequence, many efforts were conducted, both to determine the feasibility of fabricating radomes from these materials, and to improve the techniques. Recently, a number of contracts have been conducted to determine the feasibility of fabricating radomes with shapes sufficiently well-controlled that further grinding to size is eliminated. This was apparently motivated by production and cost reduction considerations.

In contrast to the above, only a limited effort has been devoted to the investigation of the basic properties of the materials involved, and the effect of additives (or alteration of composition) upon the critical physical properties. The most frequent comment ventured by those reponsible for radome development for a missile system is something to the effect that the

radome is about to become a limiting factor in the missile design, for no materials are available beyond aluminum oxide, Pyroceram,and fused silica. This may be true, but it is nearly impossible to uncover a contract that deals exclusively with material synthesis, particularly one that is tied into an active radome system or future requirement. Many of the major contractors have internal development programs associated with materials, but these are usually concerned with the optimum means of fabricating a radome from a given material.

The majority of the information available in this survey concerned only those bodies that were offered in commercial use. In the case of isolated unique materials, only a limited amount of information was generated concerning the material properties and this was only in connection with the specific application of interest to the investigator. Data concerning dielectric characteristics at 60 cycles are of no real value to a radome design engineer, for the dielectric characteristics of materials are a complex function of frequency. Further, the limited amount of data that are presented has been obtained by crude techniques designed only to obtain relative values for comparison purposes. Often the data that are reported have been taken by techniques that are really not applicable to the material in question. Typical of these would be the measurement of the dielectric characteristics of ferro-electric materials at microwave frequencies with no consideration of the fact that the dielectric permeability is not 1.0. If this is done, the measurement techniques cannot possibly yield valid data, since,in general,these measurements are based upon a permeability of 1.0.

Still another factor that enters into the study of data concerning unusual materials of a nonmetallic inorganic refractory nature, is that these values are almost invariably measured only at ambient temperature and there is no indication of ability to survive or retain characteristics in an elevated temperature environment. Again, only one or two properties are reported.

1.4.2 Gross Value of the Product

As the use of nonmetallic inorganic refractory materials for radome fabrication has grown in popularity over the last five years, numerous discussions have centered around the question of financial support for materials development. This is, of course, always a controversial topic.

More often than not, the materials supplier feels that the costs of materials development are the responsibility of the agency or contractor desiring to modify the given material.

Conversely, the consumer is quite correct in assuming that his materials supplier will profit from any procurement based upon the improved materials, and therefore the supplier should bear the financial burden for materials development.

Consequently, the Government sponsors are placed right in the middle, and often find it necessary to arbitrate such a situation. In the majority of instances, such agencies are eager to fund basic research programs in the area of materials development, but often the budget assignments and restrictions are such that funding can only be financed on a specific missile prime contract. If this is the case, it becomes necessary to convince the prime contractor that a given development is sufficiently needed to warrant diversion of a portion of the total system funds. This frequently results in the award of only those contracts that are associated with materials fabrication techniques, rather than materials research.

A review of the annual survey of manufacturers presents an interesting observation. The gross sales of the materials supplies for 1963, representing only electrical uses of nonmetallic inorganic refractory materials, amounted to 200 million. This did not include pottery china, but was confined to such items as electronic tube insulators, switch wafers, or spark plug insulators.

A gross sales potential of this magnitude quickly points up the fact that the current production market for radomes manufactured from these materials is quite insignificant in dollar value. Obviously, an accurate total of the dollar expenditures for radomes over the last 9 years would be almost impossible to tally, for much of the cost is a hidden expense of the prime missile system. However, it does not take much imagination to make a calculated guess at the total expenditure during this period for both materials research and fabrication development. Most certainly, all of these funds totaled would represent only a small fraction of the income for only a single year realized by a company from other sources. This is not to say that a materials supplier does not realize any profit from the fabrication of radomes.

The figures above are not discussed to provide arguments for either missile contractor or materials supplier, but rather to present a more complete description of the radome industry with respect to the overall use of nonmetallic inorganic refractory materials. It is emphasized that the financial aspects of this industry are mentioned only to indicate the basis for at least a portion of the current philosophy of material suppliers regarding their attitude toward radome development and supply.

1.4.3 Advancement of the State of the Art

By 1958, the bodies readily available for fabrication of radomes had been clearly established. In the case of aluminum oxide, bodies with a purity as high as 99.5% could be obtained, and radomes made from Pyroceram were being made from the Corning formulation designated as 9606. At the present time, it is possible to procure an aluminum oxide radome from additional sources, but the material used to fabricate these radomes, and the actual fabrication techniques are no different than they were six years ago. This does not mean that the fabrication process requires refinement or modification, nor does it mean that aluminum oxide is not a satisfactory material.

Similarly, radomes manufactured from Pyroceram are still made with formulation 9606 by the same techniques as previously used. Again, Pyroceram is a useable radome material. Both of these materials have been used in production for a number of years. There are recent indications that the Corning Glass Works is about to offer an improved Pyroceram material for radome fabrication, but there has been no evaluation of this material by the missile contractors to date.

During the last five years, the technology of fused silica has been developed to the point that it is now possible to depend upon this material for the manufacture of radomes in addition to the two materials that were available in 1958.

Beyond this point, only very limited advancement has been made in the utilization of nonmetallic inorganic refractory materials for elevated temperature radomes. The properties of beryllium oxide, for instance have been better defined at elevated temperatures. This material is able to withstand much higher temperatures than any of those materials currently used to fabricate radomes. The missile contractors, however, do not feel that there is sufficient advantage to be gained in its use to justify funding of a development program for the fabrication of a prototype radome for electrical and thermal evaluation. This philosophy is, of course, based upon the requirements of active missile contracts and may be changed as new procurements are issued for future generations of missiles.

The reasons for only marginal progress in the development of radome materials are difficult to establish accurately. There are several factors contributing to this situation that most certainly enter into consideration, but the total analysis would seem to be dependent upon the individual agencies and contractors involved.

The major difficulties associated with materials development for this application are undoubtedly due to the nature of the materials themselves, and the environments in which they are exposed. One of the foremost considerations in normal structural design is the science of failure analysis. This is a logical means of improving material performance. In the case of a plastic or metal, examination after test will clearly establish the point at which mechanical failure was initiated, and allow the definition of the actual failure mechanism. When a radome fabricated from a nonmetallic inorganic refractory material does not survive the environment, the failure is catastrophic. Because of the brittle nature of these materials, there are not enough fragments left to tell anything, other than the fact that its performance was inadequate.

The need for elevated temperature material characteristics is another important parameter in materials development. The facility to accomplish all of these tests is expensive, and such data are not readily available, for there are only a limited number of these facilities in industry today. Consequently, if a development program is conducted on a minimum funding basis,

it is frequently impossible for the contract to bear the burden of such evaluations, and the tests are eliminated from the program, or made on such a limited basis as to be of little use beyond the immediate project.

Even more expensive to provide is the facility to simulate the actual missile flight environment for laboratory evaluation of a radome to determine survival. This can be still further complicated if one were to attempt instrumentation of a boresight range so that transmission characteristic could be determined with the radome at operational temperature. As a consequence of the experimental difficulties associated with the total evaluation of a radome, it is extremely difficult to establish a set of materials property criteria that can be used for basic materials evaluation, which will allow radome design based upon property information alone.

This has resulted in an acceptance criterion for nonmetallic inorganic refractory radomes based upon actual flight performance. Those radomes that are procured after this are then strictly controlled to insure the same electrical and mechanical tolerances.

It appears at this time that the presence of delivery schedules for missile systems has caused the industry to reach the point at which the techniques for fabrication of radomes from nonmetallic inorganic refractory materials are well defined and adequate for the materials available in normal production, but that consideration of materials beyond this point has not been supported by an adequate number of active programs in basic materials development to provide the basis for a significant improvement in the near future.

Currently, there are a number of developments in the area of radome technology that show promise for application in future missiles during the next five to ten years.

In the last section of this report, the possibilities of fused silica as a radome material were discussed. The results of Contract AF 33(657)-11504, presently in progress at Georgia Institute of Technology, may provide the basis for production radomes. This program is for the development of a radome to be used in conjunction with the Trailblazer missile experiments. Melpar believes that the objectives of this program, which are to define the method and procedure to insure propagation during an actual re-entry of a nose cone into the earth's atmosphere, are very closely associated with ten long-range objectives presently being strived for in the development of nonmetallic inorganic refractory radomes. A minimum of three Trailblazer shots are scheduled for the near future. Two of these will carry conventional radomes fabricated from ablative materials. The third will carry a radome fabricated from fused silica. Although this is being done in an attempt to isolate the effect of ionized ablative materials within the plasma sheath surrounding a radome during re-entry, the fused silica radome will be subjected to a very extreme environment, and its performance will provide an indication of future success on other missiles.

AMC is currently sponsoring AF 33(657)-10111 at Narmco Research and Development Company. This program as discussed in the previous portion of this report is associated with the manufacture of composite radomes by mosaic techniques. If this program proves successful, the radome industry will have at its disposal the means of fabricating very large structures from nonmetallic inorganic refractory materials. The real success of such radomes in application is still questionable, for it remains to be seen if this type of construction will eliminate any of the problems of thermal shock and temperature capability, but there is a good chance that this technique can be modified in the next decade to provide the basis for a versatile radome fabrication method.

During the first year's effort, six grades of Al_2O_3 plus additional BeO adhesives were investigated for use on this program. Four were satisfactory. The BeO, although satisfactory, was eliminated on the basis of handling. All dense Al_2O_3 bodies with greater than 97.6% purity were acceptable from an electrical standpoint.

The current efforts of Interpace to develop a sandwich radome structure shows promise as a means of improving thermal shock characteristics, and providing a broadband capability not presently available. It appears quite likely that the technology associated with the development of low density nonmetallic inorganic refractory bodies will advance sufficiently to provide the capability of making a satisfactory foam from almost any refractory composition. At the present time, it is possible to make foamed structures not only from Al_2O_3, but also from Z_rO_2, ThO, and MgO. Work is also in progress to develop a useable foam from silica glass. The development of a foamed BeO body may serve to provide additional elevated temperature and thermal shock resistance capability beyond that obtained from the present Al_2O_3 foamed interlayer structure.

INTERPACE has worked on this process since 1959. It appears that the methods of controlling both the dense skin and the 94% Al_2O_3 foam interlayer are now well defined. A number of experimental radomes have been fabricated and it is anticipated that several of these will soon be evaluated for both electrical performance and thermal shock resistance.

In still another instance, a number of material manufacturers have recently been experimenting with the fabrication of aluminum oxide in the form of a corrugated sheet. This immediately suggests the development of a honeycomb-type radome from nonmetallic inorganic refractory materials. In general, honeycomb construction is used as a means of achieving a high strength-to-weight ratio for self-supporting radomes. Beyond this structural advantage, a honeycomb construction offers mostly problems; the nature of a honeycomb material is such that electrical design of radomes is difficult, and it would be expected to exhibit poor thermal shock resistance. As a consequence of the problems associated with them, it is doubtful that radomes fabricated solely from nonmetallic inorganic refractory material

honeycomb construction will be capable of providing satisfactory performance. The potential of this type of construction, then, lies only in its use for the fabrication of extremely large radomes - in this instance, the non-metallic inorganic refractory material honeycomb would be used as a relatively lightweight structural inner shell. The outer shell could then be either a dense skin of one of the dielectric refractory materials, such as (Al_2O_3 or BeO), a light weight foam, or a combination of both.

Beyond these current activities, it has been well established that a critical need exists for the development of a material or method of utilizing current materials to extend the upper limit of both thermal shock resistance and temperature capability. Those missile systems presently in the concept stage of development cannot be limited by a lack of materials development if our missile program is to satisfy the future needs of our national defense.

1.5 Overall Importance of Materials in the Next Ten Years

In the preceding section, the four techniques showing the most promise in providing radomes suitable for flight on future generations of missiles were discussed. With the exception of the current studies concerning radome fabrication from fused silica, all of these developments are associated with fabrication techniques using existing nonmetallic inorganic refractory materials.

This is typical of the situation that arises when designers find that the materials used in fabrication are approaching their limit of capability, and there is no substitute material available. When this happens, the designer must then find a means of providing the material with a somewhat artificial extension of capability gained only by using the material in an unconventional manner. To a lesser extent, this was the situation that existed at the time the first large radomes were fabricated from nonmetallic inorganic refractory materials, even though the materials had the temperature capabilities needed, industry had not fully developed the necessary fabrication techniques.

At the present time, however, the radome industry must face the fact that the current materials themselves may soon become the limiting factor in further development. True, the currently available materials are satisfactory for use on the existing generation of missiles, and appear to be equally suited to application for the next generation, but beyond this it is difficult to project the real needs. This is not so much an indication of lack of direction on the part of the advanced weapons systems planning as it is a lack of information concerning the true ability of various materials to survive the future environments. Missile weapons systems are procured by the Government on the basis of operational performance. Within the limits of economy, then, the design and manufacture of these missiles in accordance with the performance specifications is the responsibility of the contractor. It is quite likely, therefore, that additional information concerning the ability of materials to survive high temperature environments

has been obtained during the performance of these contracts, but is contained only in obscure internal reports. Certain of the prime missile contractors have conducted radome tests in wind tunnels, but these tests were not extended beyond the anticipated environment into more extreme trajectories. As a result, the test is a go/no-go type which is adequate from a performance criterion standpoint, but does not establish the ultimate performance capability. These reports are also closely associated with classified design information and are not available for general consumption.

A study of the data presented in this report should serve to identify the real importance of nonmetallic inorganic refractory materials to the future of elevated temperature radomes. Two factors become quite important: the lack of available data and the inability to properly identify the material composition for the data that is in the literature. It is not enough to define a material as alumina, for alumina is not always pure alumina. Typical of this is the common use of alumina for furnace tubes. Manufacturers will normally rate the commercially available products at approximately 2000°F if it is made from 85% alumina, while the 98% alumina body is expected to perform satisfactorily at temperatures slightly above 2900°F. In addition, examination of the data presented in this report shows a great difference in the corresponding electrical and physical properties.

During the coming ten years, then, the materials themselves will become increasingly important, as the emphasis turns from the criteria of application performance to one of basic materials development with an effort to modify the composition in such a manner that a marked improvement in high temperature performance can be realized. It will be increasingly important to select materials for an application based upon the ability to withstand the most severe environment. It will be essential to compromise on the characteristics in both temperature ranges, for it will not be possible to find a universal material that performs equally well in any and all temperatures. In fact, it may very well be necessary to settle for something less than optimum performance during those periods of flight when the thermal conditions are far less severe than during the moment of maximum thermal stress.

Basic materials will hold the key to the future advancements of elevated temperature radomes. Fabricated from the nonmetallic inorganic refractories. The ultimate utilization will not be possible without an intensive effort to characterize the materials well enough that the designers can benefit from the advantage that this class of material offers in the elevated temperature environments, and at the same time learn how to utilize them in such a manner that the undesirable characteristics do not limit the total usefulness. This must be supplemented by basic materials development research efforts directed toward the improvement of all of the material properties vital for use as radomes.

1.6 Availability of Material Property Information

The title of this report clearly describes the ultimate zone of this program. As discussed earlier, the intention of this effort was to compile the available data concerning the use of nonmetallic inorganic refractory materials for radome application in order that the present state of the art for this usage could be defined. This report does accomplish the objective as stated. It has been possible to compile that data on material properties that is available, and to augment this with visits to the facilities involved in radome use or development.

During this contract effort, 7000 documents were reviewed for information. This number included DDC documents, papers, personal communications, Government reports other than DDC, DMIC memos, bibliographies, patents, and text books. Twenty-four facilities were visited during the contract period.

It is the undefined goals beyond the assigned task that require further consideration. When this program was initiated, Melpar & ASD desired to provide more than just a survey of the state of the art. There is a definite need for information that would allow the selection of the best material within this class for use in any radome requirement. Further, future development of missile systems now in the concept stage must rely upon scientists' ability to establish a needed sense of direction in materials development in order that final performance criteria need not be arbitrated by materials limitations.

This contract effort succeeds in pointing out the lack of true materials development. Examination of the contract efforts listed in section 1.3 provides an explanation for this lack. During the initial transition from plastic materials to the nonmetallic inorganic refractory types for use at elevated temperature, radomes work was carried out at a rather hurried rate, to satisfy an operative need. As a result, the contractors could not be concerned with whether or not the material was optimum for the application; instead, the only real criteria was performance. In the majority of instances the contract efforts concerning the use of nonmetallic inorganic refractory material for radomes were devoted to the techniques of fabrication. In a sense, the contractor recognized the need for those types of materials in construction and set about to find a way to fabricate satisfactory radomes from them. This meant that little if any attention was given to a real evaluation of the material as a dielectric, or structural material. Instead, the criteria for acceptability became two-fold. First, a given material had to survive a missile flight, functioning electrically; and once this had been accomplished, the criterion became one of uniformity of material from a given supplier. Little concern was evidenced if one supplier fabricated a radome from a basic material that was slightly different from another as long as each manufacturer produced the same body each time he filled an order. This is to say that if a body was uniform, the missile contractor was willing to adjust his grinding operation for each supplier.

The data presented in this report demonstrate that there is a difference between the materials supplied by various manufacturers. This is partially due to the fact that for many years the fundamental yardstick used to categorize a nonmetallic inorganic material was the "percent of the major oxide." Aluminum oxide is not supplied in terms of its chemical composition, but rather by the manufacturer's body trade designation coupled with a knowledge of the fact that it is an 84%, 90%, or 99% body. Within this one limit, the manufacturer can use his own discretion as to binder, or other additives to promote the fluxing and sintering of the composition of his choice. The selection of constituents, then, will allow an individual to work with a firing temperature that may best suit his manufacturing facility, or utilize a different type of pressing equipment to accomplish the initial forming.

It is well known that these small variations in chemical composition are extremely important in the overall process. This is clearly demonstrated by the fact that during this contract, the majority of the materials manufacturers would not release the chemical composition of their bodies. This information was considered proprietary by each company and, therefore, vital to their economic interests. This reasoning can be understood, for if the composition is unique and capable of yielding a body that has numerous advantages over that of a competitor, one must honor their wish in not making this information public. It is easy to scoff at this attitude, and state that the lack of material identification by composition imposes a severe limitation upon the value of the information presented in this report. However, the knowledge of material identification by composition in itself would only be a partial solution, for it would still not answer the question as to what the properties of these bodies would be if these percentages of composition were varied, even only slightly. Furthermore, very little information concerning the basic dielectric, thermal, and mechanical properties is available at all.

Several factors enter into the general lack of materials development and characterization. One of these is most certainly the economic consideration. On one hand, the missile contractors choose to lay the full responsibility of materials development upon the manufacturer, feeling that if a supplier wishes to succeed, he must expect to constantly improve his basic product line. Thus, when the need for a more exotic material presents itself, it will merely be a matter of making a radome from a material that is now a stock item. The materials supplier, however, does not share this view. He feels that radome production represents only a small portion of his gross business, and that he cannot afford to invest company support in development of either basic materials or new fabrication techniques prior to the need of the missile industry. This situation is further complicated by the fact that materials suppliers are not sure what the criteria for materials characteristics should be.

One of the contributing factors to the situation is the fact that the nonmetallic inorganic refractory radomes used to date have realized impressive success in operation.

Radomes fabricated from these materials have been in use for some time on several operational missile systems. To date, there has not been a single missile failure that can be traced to the radome itself. Further, in the evaluation stages of these various contracts, many radomes have also been flown. In only one instance has a failure occurred in a radome during flight. This was reported by General Dynamics. During the early phases of one of their prime contracts, the radome failed on two successive flights. This was traced to the thermal shock, and the staff of General Dynamics was able to establish the fact that the radomes, as received, were not evaluated for thermal shock resistance. The acceptance criteria of the radomes were changed such that each radome is now subjected to a thermal shock of 125 percent of flight value after fabrication as a blank. If the radome survives this shock, it is then ground to final dimensions. Prior to shipment to General Dynamics, it is again tested in thermal shock - this time to 100% of the flight trajectory shock. Since that procedure has been established, no further failures have been experienced.

The fact that radomes fabricated from nonmetallic inorganic refractory materials have demonstrated such a high level of performance and reliability seems to indicate that, in almost all cases, the materials are actually capable of even more severe environments. Furthermore, the trajectories of the generation of missiles presently in the prototype stage are only slightly more severe. Consequently, it appears that existing materials will be adequate for most uses envisioned for the remainder of this decade.

Melpar concludes, therefore, that there is a need for basic materials development in the near future, if the requirements of operational missile systems for the 1970 era are to be met. The program currently being performed by the Georgia Institute of Technology, mentioned in section 1.4 of this report, has some promise. In this approach, a number of experiments are being conducted to ascertain the effects of additives to the basic composition on the electrical, mechanical, and thermal properties as a function of temperature.

2. IDEAL RADOME MATERIALS

The primary objective of this study is the compilation of the currently available data concerning nonmetallic inorganic refractory materials with respect to the fabrication of radomes for use at elevated temperatures. The basic elevated temperature characteristics for each material investigated are presented in this report. All data were carefully reviewed and analyzed and only data of known reliability are included. Thus, the reader is presented with property data that will serve two purposes: (1) provide a knowledge of the relative ability of a given material to perform satisfactorily as a radome under various temperature conditions, and (2) allow an immediate appraisal of the state of the art for each material.

It is not the purpose of this report to treat in detail the basic principals governing the electrical and structural design of an operational radome; rather, this information is presented only to provide a knowledge of the materials themselves and their performance as a consequence of exposure to the environments experienced in use as a radome. Obviously, the application of these data to radome design requires a complete knowledge of all the electrical and mechanical requirements imposed by each specific vehicle. To provide an elementary understanding of the overall complexity of radome design, this report includes a very brief survey of the electromagnetic and structural requirements in Sections 5 and 6, respectively. For a detailed consideration of all of the aspects of Radome Design, the reader is referred to WADC TR 57-67 and the current revision of this document.

The application of theory to practice is entirely dependent upon the ability to fulfill each of the boundary conditions imposed by the mathematical model. This can only be accomplished through careful consideration of those materials and components available that can be used to implement the theory, and the selection of those most nearly suited to the theory. In the final analysis, any product is the result of a series of compromises and its ability to perform the desired function is completely dependent upon the extent to which it was necessary to arbitrate the design criteria when the functional unit was assembled. This situation becomes quite apparent in the case of radome design. The radome becomes the last element in a long series of compromises that must be made.

Assuming that the designer has been able to achieve a completely satisfactory design up to and including the antenna itself, based upon available material and electrical power, another condition must be satisfied. This antenna has been designed upon theory assuming free-space conditions that have been further modified to account for the presence of an atmosphere; now it must be protected from still another environment which it will encounter in its use. The function of a radome is well defined--it must provide maximum protection and, at the same time, have a minimum effect upon the propagation characteristics of the electromagnetic energy transmitted by the antenna. Frequently, a radome is necessary in the performance of a ground-base

antenna system. In some instances, this is a requirement to protect the antenna from the weather elements of rain, snow, etc. In others, it is a result of the use of an antenna so large that a constant temperature and humidity atmosphere must be maintained to retain critical dimensional stability, by avoiding any changes in configuration due to thermal expansion.

In the case of a missile radome, the antenna must be protected from much more severe environments. The radome must be capable of providing the desired protection for an antenna, and, at the same time, it must disturb the electromagnetic field as little as possible. Any radome must necessarily introduce an interface and physical material into the direct path of an electrical field of an antenna. The total ability of the radome system to direct this energy accurately is then dependent upon the dielectric properties of the material used to fabricate the radome.

The ideal radome material, based upon electrical considerations, is one that is very transparent to electromagnetic energy, such that a minimum of power is lost in transmission through this material. The actual value of the dielectric constant of the ideal radome material is of little concern; however, both the dielectric constant and its associated loss tangent should experience no change in value as a consequence of use at different frequencies or temperatures. Physically, the ideal radome material should not change in size or shape upon exposure to elevated temperatures. Since the dielectric constant of the radome material determines the final shape of the transmitted radiation pattern, it is essential that the material be homogeneous. Isolated areas introducing a dielectric constant different from that of the rest of the radome will result in the distortion of this portion of the radiation pattern.

Structurally, the ideal radome material must retain physical integrity throughout the entire flight trajectory in the presence of the resulting aerodynamic loading and thermal stresses.

Logically speaking, no single material can possibly satisfy all of these requirements, since no material can behave as free space and, at the same time, afford physical protection. Design, then, becomes a matter of selecting a material that will reasonably satisfy both the electrical and physical requirements.

2.1 The Comparison of Existing Materials with the Ideal Model

In many instances it is possible to accomplish easily a comparison of material properties with application needs since the standards or limits of operation are clearly defined. Moreover, each fundamental element of the material requirements can be separated from the rest with little or no consequence. Such situations usually arise in the case of operation under nearly static conditions. The large ground radome would be a good example of this, for the radome itself experiences only a small change in temperature and,

as a result, none of its electrical or physical properties can be expected to change drastically from hour to hour or season to season. The designer for such an application can then easily select an ideal set of electrical and physical properties.

The physical size is merely that required to enclose completely the antenna system that is to be protected. The size considerations allow an immediate calculation of the structural load caused by wind, rain, or snow. The additional calculation of the structural load resulting from the weight of the radome structure itself is dependent upon the total size, whether or not a monolithic radome can be used, or if it is necessary to reinforce the radome through the use of ribs, or a fabrication technique such as the use of a honeycomb material. The basic knowledge of the radome size, then, allows one to establish quickly a model of the ideal material. If the radome is to be small, the obvious choice is a thin-wall design. This will provide optimum transmission characteristics with a low dielectric constant, and a low dielectric loss. As long as the loss tangent is less than 0.01, the transmission of the total system will be satisfactory. The physical requirements can be determined in terms of the tensile, flexural, and compressive strengths that will be experienced in use. Once this list of properties has been established, the candidate materials can then be compared directly with the model by the examination of each individual characteristic of both.

The extension of ground-base radome design to elevated temperature use could be accomplished with comparative ease, if the radome under consideration were to operate only at one elevated temperature, and it could be assumed that the temperature of the radome would be established at the operational temperature through a slow heating process. This condition would also represent static application, and an ideal radome material model could once more be defined, based upon the static operational environment. In this instance, the electrical properties of the model would again be based upon the necessity of a loss tangent of less than 0.01, in order to achieve satisfactory transmission, and the dielectric constant would once more be determined by the specific radome design selected to realize structural integrity. The ideal model would than have a set of physical and electrical properties associated with it that could be compared with those of the candidate materials. In this instance, a knowledge of the basic electrical and physical properties as a function of temperature would allow a direct one-to-one comparison with each property of the ideal model at any one temperature.

Unfortunately, the missile radome does not operate under static conditions. During its flight trajectory, the missile is subjected to aerodynamic drag that causes the radome to heat up. These same aerodynamic forces impose high levels of structural stress upon the radome. Both the heating and structural loading are extremely transient in nature. The addition of a transient temperature environment complicates the identification of an ideal radome material still further, for it is now necessary to include into the basic material requirements not only a knowledge of the

radome type, but also a detailed knowledge of the specific missile flight trajectory. This means that the selection of a material for the fabrication of a missile radome can only be accomplished after consideration of the interaction of the thermophysical properties of the material resulting from the transient heating. As a consequence, it is impossible to base the design of a radome for missile application solely upon a knowledge of the material properties as a function of static temperatures. The design of each missile radome must be accomplished as an individual case and no single ideal radome material can be considered as typical for all missile radome applications.

It must be emphasized that any attempt to select a nonmetallic inorganic refractory material for the fabrication of a radome for use at elevated temperatures cannot be accomplished without detailed consideration of the specific missile operational characteristics. Section 6 of this report presents a typical example of the manner in which each of the material characteristics must be analyzed to insure satisfactory performance of a radome fabricated from these materials.

Each of the inorganic refractory materials is unique, and must therefore be individually considered. The reader's attention is called to the fact that the data compiled during this study are presented as individual plots, or data points. This has been done to prevent the possibility of anyone using average values as ultimate standards of performance. The reader is cautioned against such a mistake, for the data that are presented in this report clearly demonstrate the existence of significant differences in materials produced by different manufacturers and fabrication techniques. The extreme interdependence of all of the material characteristics must also remain foremost in the mind of the designer.

In the discussions that follow, the general characteristics of nonmetallic inorganic refractory materials as a consequence of exposure to elevated temperatures will be discussed in very general terms. No attempt is made to relate these characteristics to any one missile system; rather, this information is presented to draw attention to the basic differences between these materials and the types of problems associated with their use.

The first concern in the selection of a radome material must necessarily center around the dielectric characteristics. Since the dielectric constant must be something in excess of 1.0, and the material must have a dielectric loss associated with it, immediate consideration must be given to the specific radome design type. The characteristics of a thin-wall design, as discussed in Section 5 of this report, are very attractive in terms of the overall propagation efficiency. Unfortunately, in the case of the nonmetallic inorganic refractory materials, the structural integrity of the radome would be poor, and a thin-walled design is not usually practical. Sufficient structural strength is normally obtained if radomes fabricated from nonmetallic inorganic refractory materials are based upon a half-wave electrical wall thickness (also discussed in Section 5 of this report). Since the total wall thickness of a half-wave radome design is inversely proportional to the

one-half power of the dielectric constant, it is desirable to have a relatively high dielectric constant to prevent the radome from becoming extremely heavy. In this respect, the dielectric constant of most of the available nonmetallic inorganic refractory materials is satisfactory. In almost all cases, the dielectric constant is in excess of 5.0, and frequently as high as 9.0. Again, the loss tangent must be less than 0.01 and, since almost all of the inorganic nonmetallic refractories exhibit a loss tangent approximately one order of matnitude less than this, they are quite satisfactory.

The dielectric characteristics of the nonmetallic inorganic refractory materials all change significantly at elevated temperatures. The specific design of the radome and its associated antenna determine whether or not this change is prohibitive. In many cases, the loss tangent at microwave frequencies is still less than 0.01 at temperatures as high as 2000°F, which should still allow adequate transmission. The change in dielectric constant, however, may result in an effective electrical wall thickness so different from the half-wave design thickness as to reduce the transmission below the required level.

The second broad category of materials properties that must be considered is that of structural strength and the interaction of each of the individual properties as a result of the thermal characteristics and the exposure to transient thermal environments. Earlier in this report, it was stated that Melpar was directed to concentrate the efforts of this study upon the dielectric characteristics of the nonmetallic inorganic materials and the use of these materials as radomes. This direction was taken in order to avoid duplication of the two other ASD-sponsored contracts associated with the thermal and mechanical properties of the nonmetallic inorganic refractory materials. While certain of these data are presented in this report, the reader is referred directly to the final reports of those two Air Force contracts, AF 33(657)-8326 and AF 33(657)-8064, for a complete compilation of these data.

Again, the data concerning the mechanical and thermal properties of the nonmetallic inorganic refractory materials should be treated as individual characteristics, unique to a given manufacturer and fabrication process. As pointed out in these reports, the experimental techniques used to obtain these data must also be studied to ensure the significance of these data relative to any given application.

At the present time, the principal concern of the radome industry is not the ultimate strength of the inorganic nonmetallic refractory materials at elevated temperatures, but rather the ability of these materials to withstand the thermal shock experienced in normal flight trajectory. In addition to the requirement for useable dielectric characteristics, the thermal shock resistance of a material is rapidly becoming the major consideration. The importance of this factor in radome design is demonstrated by the fact that contractors such as the General Dynamics Corporation incorporate actual thermal shock test procedure into the quality control procedures for production acceptance.

Thermal shock is the consequence of the interaction of several of the basic properties of a given material. In the case of a radome, it occurs when the outside surface of the radome wall is suddenly heated to an extremely high temperature as a result of the aerodynamic drag. Since the thermal conductivity of the nonmetallic inorganic refractory materials is quite low, the inside surface of the radome wall does not begin to increase in temperature until the outside surface is very hot and a sharp thermal gradient is established through the thickness of the radome wall. The outside surface begins to expand immediately upon being heated, while the inside surface remains cool and does not expand. As a result of the differential expansion of the two surfaces, the outside surface is placed in compression and the inside surface in tension. If the resulting tensile stress exceeds the ultimate tensile strength of the material of which the radome is made, the radome will fail. The compressive strength of the nonmetallic inorganic refractory materials is much higher than the tensile strengths so that failure occurs in tension.

The seriousness of this problem with respect to high performance vehicles must not be overlooked. The current revision of WADC TR 57-67 covers this topic in considerable detail. In addition, the results of a number of sled tests conducted at NOTS, China Lake, California, are presented.

The complete study of the phenomenon of thermal shock requires consideration of thermal conductivity, thermal expansion, strength, elastic modulus and, even more important, a detailed knowledge of the thermal transfer coefficient between the material being subjected to thermal shock and the surrounding environment.[29] Since this topic is discussed in adequate detail in the current revision of WADC-TR 57-67, Melpar refers the reader to that document. In addition, the details of the heat transfer coefficient are discussed in Section 6 of this report.

Currently, aluminum oxide and Pyroceram are the only nonmetallic inorganic refractory materials being used in the fabrication of operational radomes. Pyroceram exhibits thermal shock characteristics superior to those of aluminum oxide. One of the major reasons for the present consideration of fused silica as a radome material is the fact that its thermal shock resistance is superior to both Pyroceram and aluminum oxide. Beryllium oxide has not yet been used as a radome material, but the thermal shock resistance of this material is excellent, although probably not as good as that of fused silica. Magnesium oxide is considerably poorer in thermal shock resistance than aluminum oxide. Spinel is comparable to aluminum oxide in thermal shock resistance. Boron nitride should exhibit considerably better thermal shock resistance than aluminum oxide.

Review of the property data presented in this report clearly demonstrates the uniqueness of each of the nonmetallic inorganic refractory materials. It would be well to discuss the basic properties of each of these materials in order that one may better see the role that each will play in the present and future development of radomes for use at elevated temperatures.

Aluminum Oxide. ($3.98\ gm/cm^3$) Melting Point 3630°F.

Aluminum oxide is currently being used in the fabrication of radomes for operational missile systems. The dielectric constant of aluminum oxide at microwave frequencies is dependent upon the purity of the particular body. A 99.5% body will exhibit a dielectric constant of the order of 9.6, with a loss tangent of 0.0001 at ambient. The value of the dielectric constant changes in a reasonably linear manner as the temperature of the material is increased to 2500°F, at which time the value is approximately 12.0. The loss tangent increases more rapidly, and approaches a value of 0.01 at this same temperature. As the purity of the aluminum oxide body decreases, the dielectric characteristics are lower at ambient. A typical 85% body has a dielectric constant of 8.3 and a loss tangent of 0.0010 at ambient. The dielectric constant increases to 9.5 by 1800°F, while the loss tangent is already 0.010.

Radomes are normally fabricated from a 97%, or higher, purity aluminum oxide body to realize the best possible dielectric characteristics. The tensile strength of a 99% aluminum oxide body can be expected to be of the order of 32,000 psi at ambient, while the modulus of rupture is approximately 50,000 psi. The tensile strength starts to drop off rapidly at 500°F and reaches a level of about 25,000 psi at 1600°F and 11,000 psi at 2500°F. The flexural strength, however, retains the ambient level until approximately 1000°F, at which time it drops very rapidly to 25,000 psi at 2000°F and about 10,000 psi at 2500°F. The modulus of elasticity of a 99% body, which is 51×10^6 psi at ambient, drops to 47×10^6 at 1500°F and 39×10^6 psi at 2500°F. The normal total emittance of a 99% aluminum oxide body drops rapidly from a value of 0.79 at ambient to less than 0.5 at 2000°F. The thermal conductivity of a 99% aluminum oxide body drops rapidly from a value of 0.10 cal/cm/sec°C to a value of 0.020 at 2500°F. The specific heat of the same 99% aluminum oxide body rises from a value of 0.23 Btu/lb/°F at ambient to 0.31 at 1600°F, after which it drops back down to 0.25 at 2500°F. The coefficient of thermal expansion for a 99% aluminum oxide body is 3.45×10^{-6} in/in/°F. The maximum useable temperature for a 99% body is generally considered to be approximately 3050°F.

Aluminum oxide will continue to be useable material for the fabrication of radomes to be used on vehicles that do not require high thermal shock resistance. It is doubtful that any aluminum oxide body will be capable of operation at temperatures above 3200°F, which appears to be the upper limit for even a 99.9% body. The fabrication techniques for monolytic aluminum oxide radomes are well defined and, as mentioned elsewhere in this report, its use is also anticipated both for multilayer structures using a foamed aluminum oxide interlayer and for the mosaic fabrication technique currently under investigation.

Beryllium Oxide. ($3.0\ gm/cm^3$) Melting Point 4620°F.

Unlike aluminum oxide, beryllium oxide has not yet been used as a radome material in operational weapons systems. The primary reason for this

is the expense required to develop the fabrication techniques and problems arising from its toxic nature. The dielectric constant of beryllium oxide is in the order of 6.4 for a 99.5% body at 10 gc and ambient, with a loss tangent of 0.0001. The dielectric constant increases to 9.0 at 2800°F, while the loss tangent rises to 0.0005 at this temperature. The thermal conductivity of beryllium oxide is much greater than that of aluminum oxide, exhibiting a value of approximately 0.5 cal/cm/sec°C near ambient, and falling to a value of 0.039 at 2500°F. The tensile strength of beryllium oxide is also lower than that of aluminum oxide, with a value of approximately 17,000 psi at ambient. This drops to only 1200 psi at 2500°F; however, it remains at 13,000 psi at 1500°F. The flexural strength of beryllium oxide is of the order of 37,000 psi at ambient, increasing slightly to 39,000 psi at 1500°F and then dropping rapidly to 13,000 psi at 2000°F. Beryllium oxide has a coefficient of thermal expansion of approximately 9.3×10^{-6} in/in/°F. The Young's modulus of beryllium oxide is 46×10^{6} at ambient.

Although the melting point of beryllium oxide is well above 4500°F, it is doubtful that this material will be useful much above 3500°F. While beryllium oxide has not gained acceptance as a radome material, it has been used extensively as a microwave window material for high power transmission systems. This is primarily due to its high thermal conductivity and low loss characteristics.

Boron Nitride. (2.25 gm/cm^3) Melting Point - 5000°F.

Boron nitride, like beryllium oxide, has been suggested as a radome material for a number of years. Again, however, no effort has been made to develop the fabrication technology sufficiently to make a radome from this material. The dielectric properties displayed by boron nitride are very attractive. The dielectric constant and loss tangent are about 4.4 and 0.0001, respectively, at ambient. They rise only to 4.52 and 0.0017, respectively, at 1800°F and a test frequency of 9.375 gc. At a test frequency of 4.83 gc, the dielectric constant changes from 5.1 to 5.2 upon reaching 2400°F, and the loss tangent is only 0.0002. The fact that boron nitride does not melt, but sublimes, at 5000°F should make it an excellent candidate for high temperature radome use. The major concern regarding the use of boron nitride as a self-supporting radome would center around its poor mechanical properties. The modulus of rupture for boron nitride is of the order of 10 to 15,000 psi at ambient, and this value drops off rapidly to only about 2,000 psi at 1500°F. At the same time, the modulus of elasticity is only about 15×10^{3} psi at ambient, dropping, in a manner similar to the modulus of rupture, to only 4 or 5×10^{3} psi at 1500°F. The thermal conductivity of boron nitride is comparable to aluminum oxide at temperatures below 2000°F. The coefficient of thermal expansion, however, is rather high.

Magnesium Oxide. (3.57 gm/cm^3) Melting Point - 5070°F.

Magnesium oxide also shows interesting possibilities as a material for the fabrication of elevated-temperature radomes. The dielectric constant

is 9.5 at a frequency of 9.375 gc and ambient temperature. It increases to 10.8 at 1800°F; however, the loss tangent is less than 0.0001 throughout the entire temperature range. The coefficient of thermal expansion and the thermal conductivity are both comparable to aluminum oxide. The tensile strength of an 89% body of magnesium oxide is about 15,000 psi at ambient. However, it retains this level of strength to a temperature of 1500°F, at which time it drops to 5,000 psi at 2500°F. The modulus of rupture starts at about 24,000 psi at ambient, increases to 28,000 psi at slightly over 1000°F, and then drops to 10,000 psi at 2250°F. If the dielectric characteristics of this material are as good above 2500°F as they are below this temperature, this material should be an excellent choice for development efforts to attempt to make a useable radome from it.

<u>Pyroceram.</u> (2.59 - 2.62 gm/cm^3) Softening Point 2462°F.

The half-wave wall thickness for Pyroceram is 0.683 cm at a frequency of 9.375 gc. Like aluminum oxide, Pyroceram is also enjoying use in actual production of operational radomes. Pyroceram can be used for extended periods of time at approximately 1850°F. Pyroceram can withstand a temperature of 2375°F for periods of 1 minute, and 2200°F for a duration of 5 minutes. The dielectric constant of Pyroceram is 5.65 at a frequency of 9.375 gc at ambient, with a los tangent of 0.0002. The dielectric constant increases to 5.97 at 2000°F, while the loss tangent increases to 0.0138. All of the radomes currently being used are manufactured from the Corning Glass Works' formulation number 9606. In almost all cases, the surfaces of the radomes are chemically strengthened. It is anticipated that Corning Glass will soon release a new Pyroceram material that is expected to show significant improvement in all of the properties of the 9606 formulation. The thermal conductivity of Pyroceram is slightly lower than that of aluminum oxide, with a value of 0.010 cal/sec/cm°C at ambient. This value drops to approximately 0.007 at 2200°F. The coefficient of expansion of Pyroceram is approximately 3.17×10^{-6} in/in/°F, which is also slightly lower than that of aluminum oxide. The normal total emittance of Pyroceram drops from a value of 0.85 at ambient to 0.60 at 2200°F. The modulus of rupture for Pyroceram at ambient is 36,000 psi, dropping off to 31,000 psi at 900°F, and 10,000 psi at 1850°F. The modulus of elasticity of Pyroceram is rather interesting in that it drops from an ambient temperature level of 17.4×10^6 psi to 16.6×10^6 psi at slightly over 300°F. The value of the elastic modulus then increases to 17.8×10^6 at 950°F, after which it drops rapidly to 16.6×10^6 at about 2200°F. Pyroceram has exhibited excellent performance during use on several missiles. It appears, however, that the next generation of many missiles will replace this material with one capable of surviving a higher elevated temperature.

<u>Fused Silica.</u> (1.9 gm/cm^3) Melting Point 3144°F.

The thickness for a half-wave wall fabricated from fused silica, (K = 3.84), Corning 915C, for operation at 9.375 gc would be 0.873 cm.

The dielectric constant of pure fused silica at 10 gc and ambient temperature is 3.35 with a loss tangent of 0.0023. These values increase to 3.57 and 0.0090, respectively, upon heating to 2500°F. At the present time, fused silica radomes have not been used on any operational vehicles; however, extremely interested missile contractors are considering this material for use on several new missiles. Not only is fused silica relatively inexpensive to fabricate, but it exhibits outstanding thermal shock characteristics. An additional benefit is also gained from its low dielectric constant and density, for radomes fabricated from fused silica have performed very well under conditions of rain erosion. Vitreous fused silica has a very small coefficient of thermal expansion -- 0.3×10^{-6} in/in/°F and, although the modulus of rupture is only 5,000 psi at ambient, it increases gradually to about 7,000 psi at 1900°F. The modulus of elasticity is also low, being only 10.0×10^6 psi at ambient. The thermal conductivity of fused silica is very low, being only about 4% of the value for aluminum oxide.

The fact that fused silica retains its original strength levels, although low, at elevated temperatures makes this a definite material to consider at the temperature levels above that experienced by Pyroceram. A large effort has also been devoted to the study of additives to the fused silica slip in an effort to improve mechanical properties while, at the same time, not adversely affecting the electric characteristics. The fact that fused silica will actually ablate under extreme heat is also of interest. This may point the way to a radome that will perform satisfactorily for short periods of time at temperatures in excess of 4000°F.

<u>Spinel</u>. (3.59 gm/cm^3) Melting Point 3875°F.

The thickness required for a half-wave radome wall at 9.375 gc is 0.55 cm. The dielectric constant of spinel at ambient temperature and a frequency of 9.375 is 8.25, with a loss tangent less than 0.0001. At 2400°F, the dielectric constant has increased to 10.57 and the loss tangent is 0.0102. The coefficient of thermal expansion of spinel is approximately the same as that of aluminum oxide. Thermal conductivity, however, is only about one-half that of aluminum oxide. The tensile strength drops rapidly from 18,000 psi at ambient to about 2,000 psi at 2400°F. The modulus of rupture, however, remains about the same (12,000 psi) from ambient to 1800°F. The modulus of elasticity is also about half that of aluminum oxide, starting at 35×10^6 at ambient and dropping to 20×10^6 at 2500°F. Spinel, like boron nitride, has been suggested as a radome material for many years. As of this writing, however, there has been no serious effort to use this material in the fabrication of radomes.

Numerous other materials have been suggested for radome application over the past 5 to 10 years, but no data were available to provide a basis for judging them to be good or bad.

2.2 The Necessity of Sacrificing One Property to Realize Improvement in Another

Throughout this report, frequent reference is made to the temperature dependence of the properties of a material as well as the fact that characteristic behavior is quite different for each material studied. Brittle materials, such as a nonmetallic inorganic refractory, are rather unique in that, in some instances, the material is really more useable at extreme temperatures. Although the maximum strength has been lowered as a result of such an exposure, the mechanical behavior more closely resembles that of a ductile material. This could prove to be a decided advantage in the case of certain missile trajectories. If a nonmetallic inorganic refractory radome was subjected to a trajectory that resulted in aerodynamic heating to a temperature at which this behavior is exhibited, the radome could then be pushed into a much more severe trajectory for the remainder of the flight with less chance of catastropic failure due to thermal shock.

In the case of the very high performance vehicles expected to become operational in the next decade, it may well be necessary to take advantage of still another mechanism of physical behavior at very high temperatures. This could be realized in an instance when the aerodynamic heating is almost instantaneous. In such instances, the nonmetallic inorganic refractory radome does not have sufficient time to conduct any appreciable heat through its thickness. Under these conditions, the surface of the radome would actually undergo ablation. If the trajectory of the vehicle at this point was such that its mission was accomplished, or its velocity rapidly reduced and the flight course then directed onto a path resulting in greatly decreased aerodynamic heating, the radome could possible survive the total flight without ever experiencing thermal shock in the normal sense of the term. The ability of nonmetallic inorganic materials to survive an ablative atmosphere for short periods of time has been demonstrated experimentally.

In either of these situations, it is obvious that the missile system would require a design that would allow the radar transmission characteristics to suffer from extreme attenuation and dispersion during this short period of time. It is quite likely, however, that such a sacrifice will be necessary to realize the desired tactical performance of these future missiles.

A similar compromise has been made in one of the present-day operational missiles. One of the contractors has found that the temperatures experienced in flight cause an increase in dielectric constant that is too large to be accomodated in the basic antenna design. To overcome this material characteristic, the radome is machined thinner than the design required, based upon optimum electrical thickness at ambient temperature. Once the vehicle has reached flight velocity, the combination of increased dielectric constant and thermal exapnsion characteristics results in an optimum matching of the antenna and its radome.

Examination of the data reported in the Appendix to this report will allow one to visualize a countless number of situations of a similar nature that might arise in the development of a nonmetallic inorganic refractory radome. The necessity of a trade-off is not limited to just the detailed design but is an essential part of both the material selection and the specific fabrication process. Typical of this is the fact that the final step in manufacture of any radome is the use of a corrective dielectric tape. After final grinding, the radomes are individually boresighted using antennas of the type they will protect. The localized area of slightly different dielectric constant (present in almost any radome) must then be corrected to insure that the antenna will have the required propagation pattern in actual use.

It is possible for the designer to correct a given radome design to account for those unexpected deviations of material behavior that are discovered during the initial evaluation of a prototype. This is certainly not desirable, however, for it would be much more efficient, and far less expensive, if all of the material characteristics relative to temperature and frequency dependence were well enough defined that such an instance would not arise. More important is the fact that, in some instances, the particular material might not have been selected if the material characteristics had been completely defined. True, the final application of any material to radome usage is only verified by fabrication of such a radome followed by boresight and flight evaluation, but this sequence of events could progress with more assurance and ease if the needed material property information was readily available.

2.3 Improvement of Present Materials

At the present time, the need for improved nonmetallic inorganic refractory materials to survive the future missile flight trajectories is becoming more and more apparent. Unfortunately, the information upon which future material development should be made is quite limited. In addition, it appears that the communication between the materials manufacturers and the missile contractor are not always as good as desired. Much of this arises from the fact that the nonmetallic inorganic refractory materials are still new to many persons. The processes used to produce and fabricate these materials into useable configurations are unique to this general class of materials. As a consequence, in order that the advantages of these materials may be used to the fullest extent, it is necessary to understand all of the limitations both in processing and in basic properties.

It is most important, as the future environments are increased to the 3000° to 4000°F limits, that the designers and materials manufacturers expend a greater effort to provide the materials capable of fulfilling these radome requirements.

Several factors will obviously enter into the major materials development program in the next five to ten years. One of the most important of these, which should not be overlooked, is the dissemination of the materials information.

In one instance, a missile manufacturer stated that the main reason Pyroceram was selected for a number of their applications was the fact that the information concerning aluminum oxide radomes, generated under an Air Force contract in 1958, was not made available until after the time when it was necessary to make the material selection.

It is clear that a material will not be used to fabricate something if the designer is not aware of its existence. Even if he does know of a new nonmetallic inorganic refractory, he cannot consider its application until the basic electrical, thermal, and mechanical properties are well defined. This means that it will become increasingly important to characterize fully any materials that show potential for radome applications. Full characterization must necessarily include a detailed evaluation of all properties as a function of temperature. In addition to the basic physical properties, it appears likely that a number of specialized tests will have to be devised and standardized so that all facilities perform these evaluations in the same manner. As the technique for dielectric determination at elevated temperatures has become more common, the industry has seen a marked improvement in the agreement between laboratories. The radome industry is already benefitting from the last five years' effort in this area, but further work is needed to better define the mechanical properties.

Undoubtedly, a standardized method of evaluating thermal shock will be established during the next few years. This will provide both the missile manufacturer and the materials industry with a means of determining improvements in materials as well as the relative merits of each class. This will prove to be of benefit whether it actually duplicates the condition of flight, or merely provides a comparison standard, for, at the present time, no two agencies determine thermal shock in exactly the same manner.

At the present time, Hughes Aircraft Company is in the process of initiating a program to study the thermal shock of radomes of several designs, sizes, and materials. These tests will be conducted at a number of incident thermal flux levels up to and including failure. This program is designed to establish the thermal shock characteristics in order that a standard test procedure may be written.

ASTM Committee C-25 is attempting to establish a procedure for the evaluation of the thermal shock characteristics of nonmetallic inorganic refractory materials.

An effort must be made to consider more programs of the type conducted by the Armour Research Foundation in 1959, 1960, and 1961. This program,

"Research and Development Services Leading to the Control of Electrical Properties of Materials for High Temperature Radomes," is reported in WADC TR 59-300; Parts I, II and III. During this program a number of very pure aluminum oxide bodies were prepared and the electrical characteristics evaluated. The program proceeded, then, to add controlled amounts of impurities to the aluminum oxide. Such materials as $SrTiO_3$, $SrTiO_3$-$BaTiO_3$, and $CaTiO_3$ were added in various amounts up to about 20%. The dielectric characteristics were then evaluated to determine the modifying effects of the additives. These dielectric determinations were conducted as a function of temperature. Figure 1 presents a set of graphical data showing the change in the dielectric behavior caused by various additions of $SrTiO_3$. The loss tangent of the samples that were prepared was somewhat higher than the loss tangent of a very pure aluminum oxide body. Time, however, did not allow this property to be fully evaluated.

This type of basic materials research program is one that should be pursued during the coming years. The overall properties of several 99% aluminum oxide bodies have been improved during the last five years as a result of a small addition of Cr_2O_3. The addition of this impurity allowed the manufacturer to make a 99.5% body of aluminum oxide. The current work on fused silica has also studied the addition of small amounts of impurity, and it has been possible to realize improvement in the emittance properties of this body through small additions of Cr_2O_3 and TiO_2. Certainly, this same type of detailed experiment can be conducted with such materials as Spinel, beryllium oxide, not to mention further work on aluminum oxide. Unfortunately, there is so little of this type of information available that it is difficult indeed to suggest a logical approach at this time. It is important that any programs attempting to alter the basic properties of materials characterize the resulting materials as completely as possible and insure that such information is disseminated.

Examination of the data in this report shows that there are several materials, boron nitride, magnesium oxide, spinel and beryllium oxide, that show promise as radome materials for use at temperatures well in excess of 3000°F. The materials industry must sponsor active research efforts with these materials directed first toward defining all of the properties as they are now, and then selecting the direction that would seem to improve these properties. The fact that all of these materials were suggested for radome application over five years ago has not resulted in any effort to establish from them the production methods that will allow the fabrication of elevated temperature radomes. In fact, industry has not even bothered to find out their true worth.

The future development of the nonmetallic inorganic refractory materials for radome use will best be accomplished through the application of two main objectives: (1) complete characterization of all materials throughout a broad temperature range and (2) investigation of the control of the electrical and mechanical properties of the existing materials by modification of composition.

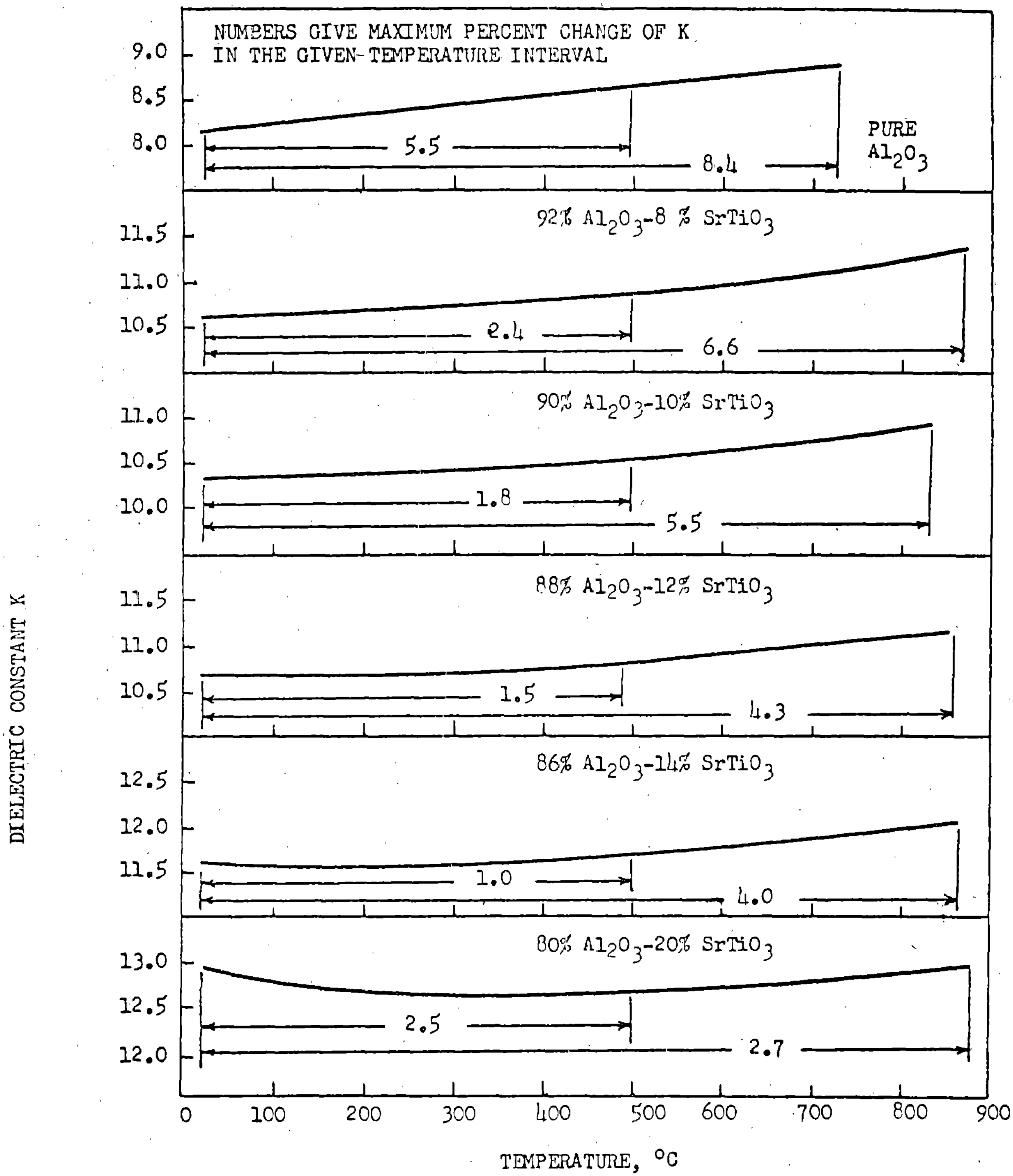

Figure 1. Temperature Variation of K at $4X10^9$ C/S for Al_2O_3 - $SrTiO_3$ Compositions

3. MATERIALS INDEX AND PROPERTY INDICATOR

The materials index and property indicator gives a quick reference to the materials, the manufacturer, the manufacturers code designation, and the properties for which data was found. Where ever a property was found, an X is placed in the appropriate square in Table 2.

In addition to this table, the materials property data Locator-Chart in the Appendix is broken down into three sections; electrical data, thermal data, and mechanical data. Each of these sections is preceded by a property indicator for the individual materials listed in that section. References are given in this listing. The letter M in the reference column indicates that the data listed was generated by Melpar under contract to independent companies and is released with their permission.

TABLE 2

MATERIALS INDEX & PROPERTY INDICATOR

MATERIAL	% MAIN CONSTITUENT	MANUFACTURER	MFG. DESIGNATION NUMBER	DENSITY	DIELECTRIC CONSTANT	LOSS TANGENT	VOLUME RESISTIVITY	SPECIFIC HEAT	THERMAL CONDUCTIVITY	THERMAL EXPANSION	THERMAL DIFFUSIVITY	EMISSIVITY	TENSILE STRENGTH	COMPRESSIVE STRENGTH	FLEXURAL STRENGTH	YOUNG'S MODULUS	SHEAR MODULUS	POISSON'S RATIO	MAX. USE TEMP.
Alumina	99.9	—	—	X	X	X	X												
Alumina	99.85	WESGO	AL-1009	X	X	X	X			X				X	X				
Alumina	99.5	Coors	AD-995	X	X	X		X	X	X		X	X	X	X	X	X	X	X
Alumina	99.5	WESGO	AL-995	X	X	X	X			X				X	X				X
Alumina	99.5	Melpar	—	X	X	X													X
Alumina	99.5	Norton	—	X	X	X		X	X	X		X	X		X	X	X	X	X
Alumina	99.5	Interpace	—					X	X	X		X	X		X	X	X	X	X
Alumina	99	Coors	AD-99	X	X	X	X	X	X	X			X	X	X	X	X	X	
Alumina	99	Silk City	99-P						X										
Alumina	99	Interpace	TC-352	X	X	X													
Alumina	99	U.S. Stoneware	610	X	X	X													
Alumina	99	Interpace	—	X	X	X													
Alumina	98	Silk City	98-D	X	X	X	X		X										
Alumina	98	American Lava	748	X	X	X	X												
Alumina	96	Coors	AD-96				X			X			X	X	X	X	X	X	
Alumina	96	Melpar	—	X	X	X													
Alumina	96	American Lava	614	X	X	X	X												
Alumina	96	Carborundum	1542	X	X	X													
Alumina	96	U.S. Stoneware	A-212	X	X	X													
Alumina	96	U.S. Stoneware	A-312	X	X	X													
Alumina																			
Alumina	96-98	WESGO	AL-300	X	X	X	X			X				X	X				
Alumina	95	Minn.-Honeywell	A-203	X	X	X													X
Alumina	95	WESGO	AL-400	X	X	X	X			X				X	X				X
Alumina	95-97	Diamonite	P-3142-1	X	X	X	X												
Alumina	94	Coors	AD-94				X		X	X			X	X	X	X	X	X	
Alumina	94	American Lava	Al SiMag 719	X	X	X	X												
Alumina	94	American Lava	—	X	X	X													
Alumina	94	American Lava	—	X	X	X													
Alumina	94	Melpar	—	X	X	X													
Alumina	90-95	Diamonite	B-890-2	X	X	X	X												
Alumina	85-90	Diamonite	P-3662	X	X	X	X												
Alumina	85	American Lava	—	X	X	X													X
Alumina	85	American Lava	Al SiMag 576	X	X	X	X												X
Alumina	85	U.S. Stoneware	A-216	X	X	X													X
Alumina	85	Minn.-Honeywell	A-127	X	X	X													X
Alumina	85	Coors	AD-85				X		X	X			X	X	X	X	X	X	X
Alumina	85	Silk City	85-D	X	X	X													X
Alumina	—	General Electric	Lucalux	X	X	X													
Alumina	—	Alberox	A-962	X	X	X													
Alumina	—	Coors	MC-2014	X	X	X													
Alumina	—	U.S. Stoneware	Al. Std.	X	X	X													
Alumina	—	National Beryllia	Alox	X	X	X													
Alumina	—	Norton	LA-603									X							
Alumina	—	Norton	RA-4213									X							
Alumina	—	Norton	Rokide									X							

TABLE 2 (Cont)

MATERIALS INDEX & PROPERTY INDICATOR

MATERIAL	% MAIN CONSTITUENT	MANUFACTURER	MFG. DESIGNATION NUMBER	DENSITY	DIELECTRIC CONSTANT	LOSS TANGENT	VOLUME RESISTIVITY	SPECIFIC HEAT	THERMAL CONDUCTIVITY	THERMAL EXPANSION	THERMAL DIFFUSIVITY	EMISSIVITY	TENSILE STRENGTH	COMPRESSIVE STRENGTH	FLEXURAL STRENGTH	YOUNG'S MODULUS	SHEAR MODULUS	POISSON'S RATIO	MAX. USE TEMP.
Beryllia	100	Coors	—					X		X			X						
Beryllia	99.7	Beryllium Corp.	Berylco		X	X													
Beryllia	99.5	—	—		X	X													
Beryllia	99.5	American Lava	754		X	X	X												
Beryllia	99.5	Coors	BD-995				X												
Beryllia	99.5	Brush Beryllia	F-1	X	X	X													
Beryllia	99	National Beryllia	Berlox	X	X	X													
Beryllia	99	Atomics Int'l	—	X	X	X	X												
Beryllia	99	Coors	BD-99				X												
Beryllia	99	Brush Beryllia	B-6-11	X	X	X													
Beryllia	98.5	Brush Beryllia	B-6					X		X									
Beryllia	98	American Lava	735		X	X													
Beryllia	98	Coors	BD-98	X	X	X	X	X		X				X	X	X			
Beryllia	96	Coors	BD-96				X	X		X				X	X	X			
Beryllia	—	Coors	BD-932	X	X	X													
Beryllia	—	National Beryllia	—	X	X	X													
Beryllia	—	Brush Beryllia	B-7-6	X	X	X													
Beryllia	—	Brush Beryllia	B-7-37	X	X	X													
Beryllia	—	Brush Beryllia	B-7		X	X													
Beryllia	—	Brush Beryllia	F-1-10		X	X													
Beryllia	—	—	—	X				X											
Beryllia	—	—	—	X				X											
Boron Nitride	—	Carborundum	—	X	X	X													
Boron Nitride	—	—	—	X	X	X	X												
Magnesia	—	Minn.-Honeywell	—	X	X	X													
Magnesia	—	Boeing Aircraft	—	X	X	X													
Pyroceram	—	Corning	9606	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X
Pyroceram	—	Corning	9608		X	X	X	X			X	X	X		X	X	X	X	X
Silica	100	Georgia Tech	—	X	X	X													
Silica	96	Corning	7900	X	X	X	X	X	X										
Silica	—	Corning	7941	X	X	X		X	X	X	X	X			X	X	X	X	X
Silica	—	Corning	7940M	X	X	X	X	X	X	X	X	X							
Silica	—	Corning	915C	X	X	X													
Silica	—	Georgia Tech	—	X	X	X			X										
Silica (Commercial)	—	American Optical	Amersil		X	X													
Silica (Translucent)	—	American Optical	Amersil	X	X	X													
Silica (Clear)	—	American Optical	Amersil	X	X	X													
Silica	—	—	—	X	X	X													
Spinel	—	Boeing Aircraft	—	X	X	X													

4. LOCATOR CHART AND PRESENTATION OF DATA

For the convenience of the user the materials property data in the appendix has been broken down into two sections -- Section A, the graphical presentation of data in the form of curves, and Section B, the tabular data used to plot the curves. The tabular data has been obtained, in the most part, from graphical presentations in the reports reviewed for this contract and should be regarded as such.

4.1 Use of the Locator Chart

In the Locator Chart which precedes Section A in the appendix, the materials are listed alphabetically by trade designation and percent of main constituent. The graphical material is found in Section A of the Appendix. The tabular data is located in Section B of the Appendix.

4.2 Presentation of Material by Maximum Available Temperature

To provide the user with a quick reference to the maximum temperature for which typical data is presented in this report, a maximum available temperature chart has been prepared. Since the bulk of this report is concerned with electrical properties, the dielectric constant, loss tangent, and volume resistivity have been presented in more detail. Representative high and low values are given for three temperatures--ambient, 500°C, and the maximum available temperature. Only maximum temperatures for which thermal and mechanical properties data were found are listed, because the absolute useable temperature of a material can only be defined with a knowledge of the duration with which a material is subjected to a given temperature. This material is presented in figure 2.

4.2.1 Criterion for Selection of Data

Materials property data was selected on the basis of reliability, material identification, and test method definition.

Dielectric data for only microwave frequencies were included because of the nature and the end application of the materials.

In some instances, where well-known investigators such as Lee and Kingery were referenced, material data was included without an exact knowledge of the test method because of their outstanding reputation in the field.

MATERIAL	DENSITY Gm/cc	DIELECTRIC CONSTANT Ambient	DIELECTRIC CONSTANT 500 °C	DIELECTRIC CONSTANT Max Temp	LOSS TANGENT Ambient	LOSS TANGENT 500 °C	LOSS TANGENT Max Temp	VOLUME RESISTIVITY Ohm-cm Amb -Max Temp	SPECIFIC HEAT Cal /Gm °C	THERMAL CONDUCTIVITY Cal. Cm./Cm.² Sec °C	THERMAL EXPANSION in/in	THERMAL DIFFUSIVITY Cm²/Sec	EMISSIVITY	TENSILE STRENGTH psi	COMPRESSIVE STRENGTH psi	FLEXURAL STRENGTH psi	YOUNG'S MODULUS psi	SHEAR MODULUS psi
									Maximum Temperatures									
Alumina 99.5	3.776	9.4-9.6	10.0-10.5	1450 °C 11.4-12.4	.00008-.0002	.00015-.0005	1450 °C .003-.01 +	1400 °C $>10^{14}$ - 10^{8}										
95.0	3.642	8.6-9.3	9.2-9.7	900 °C 10.0-10.5	.0007-.001	.001-.003	900 °C .004-.009	900 °C $>10^{14}$ - 10^{8}	1500 °C	1375 °C	1375 °C	——	1375 °C	1375 °C	Ambient	1375 °C	1375 °C	1375 °C
85.0	3.353	7.8-8.4	8.3-9.0	1000 °C 9.2-9.7	.0004-.002	.001-.005	1100 °C .01	700 °C $>10^{14}$ - 10^{7}										
Beryllia 99.5	2.902	6.0-6.4	6.25-7.1	1500 °C 9.0	.0001-.002	.00015-.004	1700 °C .0005	500 °C-1600 °C $>10^{14}$ - 10^{3}										
98.0	2.820	6.05-6.90	6.2-7.3	1300 °C 8.4	.0001-.0005	.0001-.0007	1300 °C .008	——	2700 °C	1800 °C	1000 °C	——	1900 °C	1375 °C	1600 °C	1093 °C	——	——
96.0	——	——	——	——	——	——	——	——										
Boron Nitride	2.109	4.4-5.1	4.45-5.1	1100 °C 4.5-5.2	.0001-.0003	.00009-.0007	1300 °C .0003-.01+	1500 °C 10^{15} - 10^{2}	——	——	——	——	——	——	——	——	——	——
Magnesia	3.468	9.5-9.7	10.0-10.2	1500 °C 12.1	.0001	.0001	1500 °C .01	2200 °C $>10^{15}$ - 10^{2}	——	——	——	——	——	1300 °C	——	——	——	1300 °C
Pyroceram 9606	2.598	5.63-5.81	5.65-5.95	1100 °C 5.95-6.05	.0002-.0003	.001	1100 °C .01+	450 °C 10^{15} - 10^{7}	900 °C	900 °C	1100 °C	——	1300 °C	1200 °C	——	1200 °C	——	1200 °C
9608	——	6.55	——	450 °C 6.7	.0015	——	450 °C .012	250 °C —— 10^{9}										
Silica	——	3.2-3.9	3.2-3.9	1300 °C 3.4-4.0	——	——	——	450 °C 10^{15} - 10^{9}	——	1100 °C	850 °C	1100 °C	800 °C	——	——	950 °C	——	800 °C
Spinel	3.50	8.25	8.8	1300 °C 10.5	.00015	.00025	1100 °C .0025	500 °C-1100 °C 10^{7} - 10^{5}	——	——	——	——	——	1300 °C	——	1300 °C	——	1300 °C

Figure 2 Maximum Available Temperature Data

5. ELECTROMAGNETIC CONSIDERATIONS

5.1 General Considerations

The purpose of this section of the report is to present some of the basic concepts and definitions of radome engineering in a simplified form.

The word "radome" is an acronym for radar dome. The function of the radome is quite analogous to that of the windshield. Its purpose is to protect the enclosed radar antenna, the eye of the radar system, from a hostile environment, and at the same time it must not degrade the performance of the system beyond some acceptable level.

The radar signal is electromagnetic energy which propagates in the form of an electromagnetic wave. Electromagnetic waves are made up of electric and magnetic fields which vary periodically with time. The configuration of these fields is established by the physical laws expressed in Maxwell's equations and by the material boundaries of the space they occupy. The character of radar signals is so nearly optical that we may use rays to describe their behavior.

System degradation by the radome comes about through reflection, attenuation, and refraction as the energy impinges on and passes through the radome. This is shown pictorially in figures 3 and 4. We see in figures 4 how some of the rays are reflected and bounced around inside the radome, how others are weakened or attenuated through absorption by lossy elements in the radome and terminate there, and how still others are refracted and to not leave the radome parallel to their original direction. All of these rays -- the reflected, the absorbed, and refracted -- do not reach the target and are therefore wasted. This wasted power reduces the range of the radar.

The thermodynamic requirements of missile and space vehicle missions are also quite severe. For these reasons a compromise must often be made in the design of airborne radomes between the electromagnetic requirements and the aerodynamic requirements.

Although ground-based and ship-based radomes must often withstand high winds, icing, and certain temperature extremes as a result of their use in different parts of the world, it is usually possible to give greatest attention to the electromagnetic requirements of the design. The ground-based radome will generally be spherical in shape and will be enough larger than the enclosed antenna so that the energy is normally incident upon the radome.

Aerodynamic shapes usually have conic cross sections such as ellipses, or parabolas. Airborne radomes are aerodynamic shapes modified so that they mate smoothly with adjoining parts of the vehicle. Ogives are also commonly used in radome design.

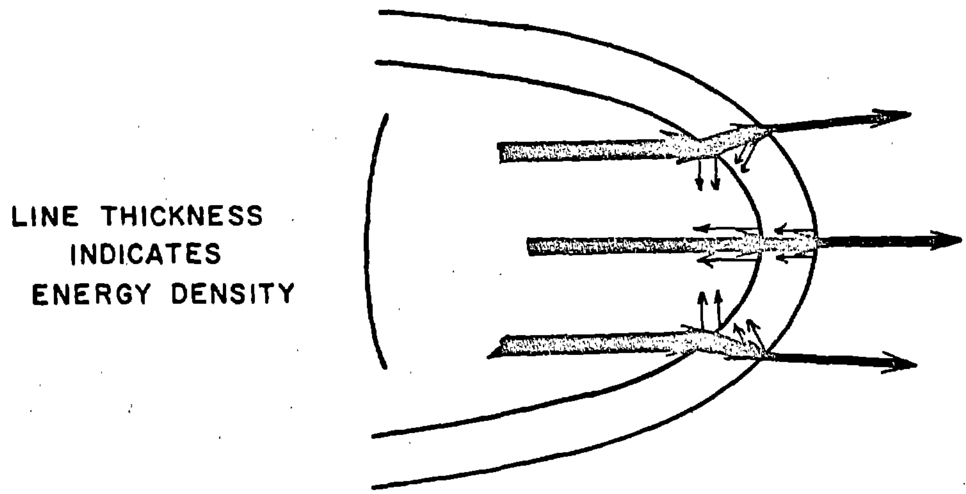

Figure 3. Scattering, Absorbtion, and Refraction of Radar Signal

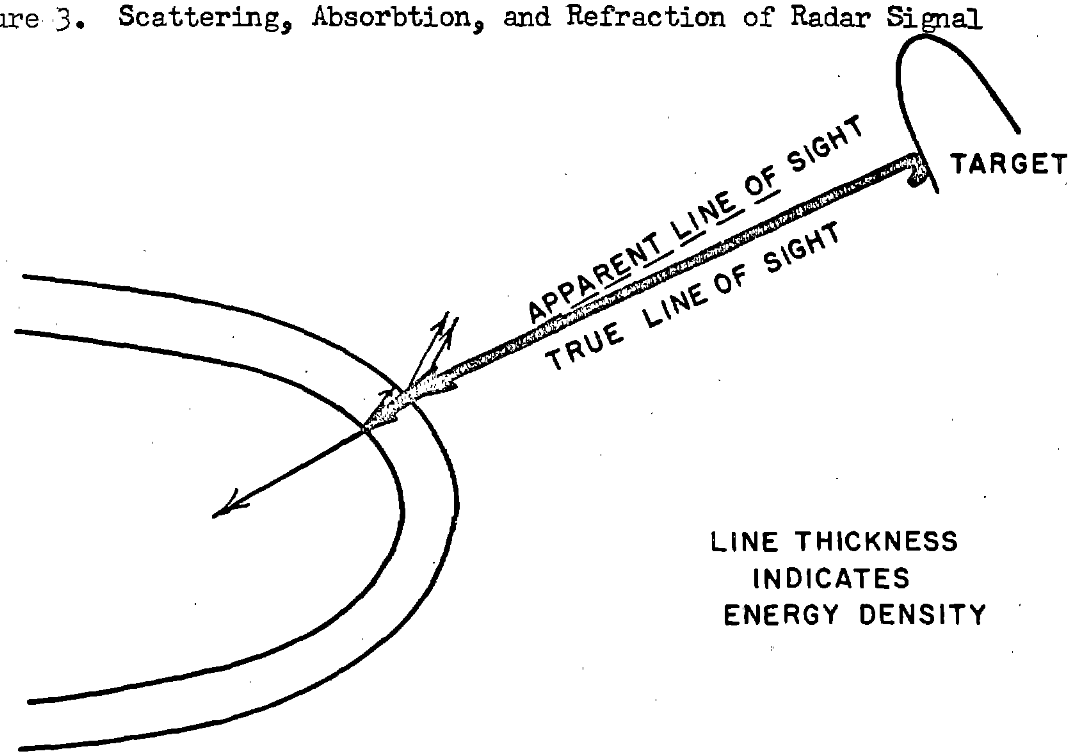

Figure 4. Scattering, Absorbtion, and Refraction of Returned Radar Signal

Small radome size along with a requirement for large scan angles causes the incident energy to enter the radome at high angles of incidence,which complicates the electromagnetic design problem.

Radome wall design falls into two classes. Both classes have names which are descriptive of the distinctive feature of the design. Solid-wall designs consist of a single layer of dielectric material, while sandwich-wall designs are usually three layers of material, although multiple sandwiches are used for applications where a large number of frequencies is used with one radome. Solid-wall radomes have two common subclasses.

Thin-wall radomes are those solid-wall radomes which are less than a tenth of a wavelength thick in the direction in which the energy propagates through them. Thin-wall radomes are useful over a broad band of frequencies but, practically, are limited to frequencies below 3000 megacycles by their physical thickness.

Half-wave-wall radomes are those solid-wall radomes which are a half-wavelength thick in the direction which the energy travels through them. Half-wave walls have many desirable electromagnetic characteristics including good performance at incidence angles as high as 80 degrees and performance which is relatively independent of polarization of the electromagnetic field. They also have adequate thickness for meeting structural requirements at most frequencies. Their major disadvantages are a result of their weight and the tight tolerances which must be maintained on both the dielectric constant and thickness. The fact that they are only useful over a narrow frequency band is also a disadvantage.

Sandwich radomes have subclasses also. The "A sandwich" is a three-layer sandwich wall construction in which the dielectric constant of the outer layers or skins is greater than that of the inner layer. The "B sandwich" is a three-layer radome wall in which the dielectric constant of the center is greater than that of the outer layers. With this arrangement, it is necessary that the dielectric constant of the skins be equivalent to the square root of the dielectric constant of the core material. This design calls for skins that are a quarter-wavelength thick. Although this arrangement has some advantages, its disadvantages, such as difficulty of fabrication and lack of weight-saving when compared to the solid-wall designs, have kept its usage from becoming popular.

Another sandwich design is the "C sandwich". The C sandwich is a five-layer design with high-dielectric-constant materials used for the skins. Low-dielectric-constant materials are alternated with high-dielectric-constant materials to make the sandwich. The C sandwich is commonly designed as a double A sandwich. It has the advantage over the single A sandwich in that it maintains its desirable electromagnetic properties with higher angles of incidence. While the A sandwich can be used to incidence angles in the neighborhood of 80 degrees, the C sandwich can be used to 80 degrees.

The high strength-to-weight ratio which can be achieved with sandwich designs, together with their competitive electromagnetic properties, account for their popularity.

In passing, it should be noted that sandwich designs with as many as thirteen layers have been used on operational radomes.

The goal of the radome designer is to provide maximum transmission, minimum reflection, and constant electrical thickness over the required range of angles of incidence, frequency, and polarization variations. In this manner the undesired effects of the radome are minimized.

The following are design techniques which are used in an effort to attain the radome designer's goals. They are based on the properties of the reflection and transmission coefficients as a function of electrical thickness. For a design to be satisfactory, the parameters of the radome-wall material should ideally remain fixed as the environment changes. That is to say, as examples, that the dielectric constant and loss tangent should not vary radically with temperature or with frequency if the radome is to be used in systems which call for large variations of those parameters.

5.1.1 <u>Single-Wall Design</u>

The simplest radome design is made of a single, homogeneous sheet of dielectric material. The maximum transmission efficiency for a lossless material occurs when the wall is an integral multiple of a half-wavelength thick. Minimum transmission efficiency occurs when the radome wall is an odd integral multiple of a quarter-wavelength thick. If the loss tangent is small, maximum transmission is obtained at about the same, although slightly reduced, thickness as for the lossless case, but the maximum transmission coefficient will be less than unity.

<u>Thin Walls -- Electrical</u>: Thin-wall designs have several desirable properties. They provide high transmission even when relatively lossy material is used. They are broadband designs in the sense that they may be used at all frequencies below the frequency at which they become a tenth of a wavelength thick. They exhibit small refraction and insertion phase shift, and the insertion phase shift is relatively insensitive to changing polarization and angle of incidence.

<u>Thin Walls -- Mechanical</u>: From the mechanical viewpoint, thin-wall designs have the advantages that they are light in weight, and the tolerances which must be maintained on the dielectric constant and thickness are not generally critical. The possibility of using a thin-wall design depends upon whether or not the thickness is mechanically satisfactory.

<u>Half-Wave Walls -- Electrical</u>: When the electrical thickness of a homogeneous radome wall is an integral multiple of a half-wavelength thick, and the integral multiplier is n, the design is known as an n-th order

half-wave wall. At the design angle, i.e., at the angle of incidence at which the wall is n half-wavelengths thick, the magnitude of the transmission coefficient is unity for both the parallel and perpendicular polarization incidence, and the insertion phase is the same for both polarizations. The insertion phase is the net phase effect produced by the radome wall, that is, the phase change that would have occurred in passing through the space occupied by the wall, if the wall had been absent, is subtracted from the phase change that occurs with the wall present . For any given angle of incidence, insertion phase increases both as the relative dielectric constant of the wall material as the wall thickness is increased. Insertion phase generally increases as a function of increasing incidence angle except at the higher angles.

Half-wave wall designs have several advantages. They have good phase delay and transmission characteristics. They perform well at high angles of incidence and can be designed for use where incidence angles as high as 80 degrees are encountered. These designs perform well as a function of the polarization of the incident energy. One disadvantage is their narrow frequency bandwidth when the relative dielectric constant is in the neighborhood of 4 or greater.

For incidence angles near grazing, that is, large angles, the best design choice is to make the relative dielectric constant of the radome material quite small. Considering more nearly normal incidence energy, design curves show that contours of wall thickness versus angle of incidence for constant power reflection approach the zero reflection contours, and these latter become more flattened as the relative dielectric constant of the wall material is increased. This indicates that for higher values of relative dielectric constant, low reflection may be obtained over a wider range of high incidence angles, but that tighter tolerances must be maintained. A dielectric constant of around 9 appears to be the best choice for minimizing insertion phase shift provided tight tolerances can be held during fabrication of the radome. Slight changes in dielectric constant or thickness may introduce tremendous electrical changes, and tolerances of the order of one-thousandths of an inch in thickness and one or two percent of the dielectric constant are necessary. Frequency bandwidth limitations of only a percent or so must also be imposed.

The comments made in the preceding paragraphs are applicable to a first-order wall design. When a higher order sheet must be used, poorer radome performance must be expected.

Data for the purposes of design is most usefully presented in graphical form. Plots of power transmission and reflection coefficients, and insertion phase delay as a function of dielectric constant, wall thickness, and angle of incidence are useful.

Lower values of dielectric constant with the accompanying lower tolerances are usually used in the design of normal incidence radomes. Variation of insertion phase is generally of interest in the design of streamlined radomes. This variation is not particularly sensitive to dielectric constant but is proportional to the wall thickness measured in wavelengths. Insertion phase variations are accentuated by quarter-wave walls and are minimized by half-wave wall designs.

Half-Wave Walls -- Mechanical: The half-wave wall design has an advantage over a thin-wall design in that it can be made structurally sound even when designed for systems employing the most used microwave frequencies. Half-wave designs have the disadvantage, especially when airborne applications are considered, of a relatively low strength-to-weight ratio. In addition, the fact that tight tolerances must be maintained on both the dielectric constant and thickness during fabrication is a disadvantage.

The structural tests to determine the strength and stiffness of half-wave designs are similar to those employed with the thin-wall designs.

5.1.2 Sandwich-Wall Designs

Electrical: The sandwich-wall design was developed to obtain an improvement in strength-to-weight ratio over the solid half-wave wall. Sandwiches are used where a thin-wall design is not structurally adequate and where a half-wave wall is too heavy. One major difference between solid-wall and sandwich-wall construction is that, for incidence angles greater than 60 degrees, the A sandwich transmits parallel polarization poorly. Also, A-sandwich transmission is fairly sensitive to skin thickness. As the thickness of the skins is reduced, the range of core thickness and incidence angles over which good transmission can be obtained is increased.

High values of the dielectric constant of the skin material are undesirable. Relative dielectric constants in the range of 4 are used. For the core the values of the relative dielectric constant are kept low.

For the most ideal performance of the B-sandwich design, the dielectric constant of the skins is chosen as the square root of the dielectric constant of the core, and the skins are made a quarter-wave thick. The main advantage of this technique accrues from the fact that good transmission efficiency is obtained regardless of core thickness.

Mechanical: As in the case of single-wall designs, strength and stiffness are the two principal mechanical requirements placed on the radome. For low density core sandwiches, the mechanical strength comes mostly from the skins. Shear in the core is an additional consideration in sandwich designs. The apparent flexural stiffness of a low-density, thin-skinned sandwich can vary over a wide range depending on the technique of fabrication. Edgewise compression and normal tension capabilities of the bond between the skin and the core must be accounted for.

5.2 Factors Peculiar to Radomes Fabricated from Nonmetallic Inorganic Refractory Material

The use of nonmetallic inorganic refractory materials for the manufacture of radomes has been brought about by the advent of big performance aircraft and missiles and the associated high operating temperatures. The design of such a radome is based on the same philosophy and follows the same procedure as the design of radomes made of other materials. These design philosophies and procedures were discussed in the preceding paragraphs. The ability of the ceramic radome to meet the structural and electrical requirements of the various designs is thus the point to consider. For example, does the relative dielectric constant of ceramic materials fall in the range required by one of the designs, and does it behave well as a function of frequency and temperature? Are the structural properties of the ceramic material compatible with the design technique to which its electrical properties are suited?

At the present time, nonmetallic inorganic refractory materials seem best suited for solid-wall designs such as the thin-wall and the half-wave-wall. For example, the half-wave-wall design requires higher dielectric constants than sandwich designs, and ceramics have relative dielectric constants in proper range. The higher dielectric constant designs imply tighter tolerances on the dielectric constant and dimensions during fabrication, however. Because of these tolerances and because of their hardness, current ceramic radomes must be ground with diamond tools, both inside and outside, to meet design specifications.

In addition to their hardness, ceramics are prone to fracture under impact. Their strength is also strongly affected by surface defects, but it may be significantly increased by hardening. Failure of a refractory oxide usually starts at a surface in tension. In spite of these drawbacks, it is highly probable that the electrical properties of the ceramic as a function of temperature will limit its use.

At microwave frequencies and high temperatures, ion jump polarization relaxation and infrared vibration absorption make major contributions to the dielectric losses. The pertinent characteristics of the relaxation processes involved are described[31] in part by their relaxation time which is proportional to

$$e^{\frac{W}{KT}} \qquad (1)$$

In Eq. (1), W is the work required to lift an ion over the potential barrier. The quantity K is Boltzmann's constant, and T is the absolute temperature. Processes which have a relaxation time approximately equal to the reciprocal of the radian frequency energy contribute to the losses. Processes with

lower relaxation time contribute to the dielectric constant. In a ceramic dielectric, therefore, the crystalline phase usually governs the dielectric constant while the glass phase is mainly responsible for the losses.

As a result of the relationships of the dielectric constant and loss tangent to the relaxation times, the loss tangent may increase or decrease with increasing frequency, but dielectric constants always decrease. In practice, unfortunately, loss tangents usually increase above 10 megacycles. In general, materials that show the lowest losses also show the least variation of dielectric constant with frequency. This fact is due to the distribution of relaxation times associated with low losses. For a more detailed discussion of the factors contributing to the loss mechanism, the reader is referred to Chapter V of the current revision of WADC TR 57-67.

More important in radome work is the degree to which the dielectric constant varies with temperature. From Eq. (1) it can be seen that, as the temperature rises, the relaxation time of a process decreases. Thus, as temperature is increased, a given process will contribute to the losses at a higher frequency. Alternatively, as the temperature is raised, a given process ceases to contribute to the losses and contributes to the dielectric constant. Therefore, if the material is low-loss over a many decade variation of frequency, it will have a relatively constant value of the dielectric constant over a wide temperature range. For best temperature stability, materials should be those which have low losses over a wide range of frequencies below the desired operating frequency. In practice, the use of microwave frequencies has some advantage from the standpoint of temperature stability of materials. It should be recalled that radomes used at the higher frequencies are more sensitive to variations of the electrical parameters.

Based on existing materials, analysis shows that high-performance boresight radomes made of nonmetallic inorganic refractory materials can be designed to have good performance characteristics at C- and X-band frequencies when thin-wall designs are used. Thin-wall K-band designs, however, do not seem structurally feasible. Study of half-wave wall designs for K-band shows them to be useful over a limited range of frequency and temperature.

5.3 Factors Peculiar to Composite Radome Structures

5.3.1 Foams

Foam materials incorporate air into a normally more dense base material. They are thus light in weight and tend toward lower dielectric constants. Because of these properties, they are used as the core material in sandwich designs. Non-metallic inorganic refractory foams have not been used previously because of the difficulties in providing suitable skins. It appears, however, that this has now been accomplished.

Loaded foams, in which very small particles of high dielectric constant or metal are included (to increase their dielectric constant to that of the skins without significant increase in weight) can also be employed in sandwich designs to simulate half-wave-wall designs.

5.3.2 Honeycombs

Honeycombs are used in place of foams as lightweight core material because they are structurally stronger. They also have some advantage in being more simple to fabricate. Some difficulty has been experienced in obtaining uniformity of the core during fabrication due to inability to control flow of the adhesive used to attach skin to core.

5.3.3 Other

Other radome materials include plastic materials such as the various resins. The different resins have various dielectric constants and loss tangents and are useful to temperatures in the range of 1200°F degrees. All the plastic resins have relatively high temperature coefficients of expansion when compared with nonmetallic inorganic refractory materials.

6. STRUCTURAL CONSIDERATIONS FOR RADOMES FABRICATED FROM NONMETALLIC INORGANIC REFRACTORY MATERIALS

The environments placed upon current missile radomes are a direct consequence of the flight trajectory, and the specific aerodynamic characteristics of the particular system. Currently, the missile manufacturers have expressed the most concern over two factors; thermal shock, and rain erosion.

6.1 Rain Erosion

The problem of rain erosion becomes a serious limiting factor for all types of materials, including the nonmetallic inorganic refractories. During recent years, the Air Force and Navy have shared cooperative efforts to evaluate the rain erosion resistance of nonmetallic inorganic refractory materials, experimentally. These tests have been conducted at the NOTS China Lake, California, sled test facility. This factor is mentioned, for it should be given thorough consideration in any effort associated with radome design and development. The detailed results of the most recent tests will be presented in the supplement to the WADC-TR-57-67, "Techniques for Airborne Radome Design," currently being completed by the McGraw Hill Publishing Company. Rather than attempt to discuss the problem at length in this report, attention is invited to the need of awareness to this problem area, with the pending publication as a reference for this information.

6.2 Thermal Shock

Melpar feels that the problem of thermal shock is one that warrants a cursory analysis. Review of the literature reveals numerous articles devoted to this topic. Usually literature discussions center around either a very general case, or the solutions to a computer program designed to predict all of the stresses and temperature gradients that occur within a radome as a consequence of flight trajectory. The purpose of this section, then, is to acquaint the reader with a general outline of the procedures used in the structural design of nonmetallic inorganic refractory radomes for high-speed flight vehicles. It is divided into four parts:

a. The Environment. The various properties of the atmosphere that directly influence the vehicle environment are briefly discussed. Then, the trajectories or mission profiles of the vehicles are considered. Finally, an outline is made of how the applied loads and heating rates are found from the interaction of the trajectories with atmospheric properties.

b. Structural Analysis. The most important aspect of high-speed flight is the temperature problem imposed by aerodynamic heating. Methods are outlined for determining the temperature distribution through the radome and the prediction of stresses caused by the temperature gradients. Finally, a brief discussion is given of the stresses introduced by the radome attachment.

c. Typical Example. A typical example of a missile radome is considered. A mission profile is selected and the temperature response and thermal stresses are computed for some typical nonmetallic inorganic refractory materials.

d. Nonmetallic Inorganic Refractory Material Problems. Some consideration is given to the particular properties which must be carefully considered in the design of ceramic radomes. Thermal shock and thermal shock protection as well as the attachment of the radome to the vehicle are discussed.

6.2.1 The Environment

Atmospheric Properties: The properties of the atmosphere that are of interest in the structural design of ceramic radomes for high-speed flight vehicles are:

a. Atmospheric temperature profile

b. Atmospheric pressure profile

c. Atmospheric density profile

d. Specific heats of atmosphere

e. Viscosity of atmosphere

f. Thermal conductivity of atmosphere

These properties have been studied extensively and there is a large volume of associated technical literature (for example, refs. 41-47). The purpose of this section is not to consider these properties in great detail but to summarize the engineering relationships required.

Up to about 250,000 feet, the atmosphere is relatively uniform and can be considered as a perfect gas so that its physical properties can be derived from the perfect gas laws and the classical hydrostatic equations once the variation of the temperature with altitude is known. Above 250,000 feet, the composition of the atmosphere varies with height, and the gas dissociates into atomic particles.

The properties of the "standard atmosphere", i.e., temperature, pressure, density and viscosity, are given in tables throughout the literature (for example, ref. 41).

6.2.2 Gas Properties

Because of the high temperatures generated by high-speed flight in the atmosphere, it is necessary to know how it behaves with temperature.

a. Specific Heats

The specific heat at constant pressure, Cp, is defined as

$$Cp = \left(\frac{dQ}{dt}\right) \quad p = \text{constant}$$

where $dQ = d(pv) - vdp + CvdT$

p = pressure

v = volume

T = temperature

Cv = specific heat at constant volume

For a perfect gas pv=RT and the internal energy of the gas is $E = 1/2\ NRT = CvT$ where N is the number of degrees of freedom and R is the perfect gas constant. Thus,

$$Cp = R \left(\frac{N}{2} + 1\right)$$

For a diatomic gas N = 5 and $Cp/Cv = \gamma = 1.4$, which is the value commonly accepted for air. Below 3,000°F the specific heat of air is not highly dependent upon temperature. However, above this temperature where dissociation takes place there is a pronounced dependence of specific heat on pressure. Values of specific heats have been computed for temperatures up to 40,000°F in reference 42.

b. Viscosity

The viscosity, μ, of a gas varies with temperature. For pressures down to 0.01 atmospheres, Sutherland's equation can be used, which for air is (ref. 46)

$$\mu = 0.245 \quad \frac{T^{3/2}}{T + 260} \quad \times 10^{-7} \quad \left(\frac{\text{lb. sec.}}{\text{ft.}^2}\right) \qquad (1)$$

where T is given in degrees Rankine. Below 0.01 atmosphere, viscosity decreases with decreasing pressure and approaches a linear relationship with pressure to 0.001 atmosphere. This relationship is discussed in reference 43. Below 0.001 atmosphere, particle dynamics must be considered (reference 44).

c. Thermal Conductivity

The thermal conductivity of a gas can be related to the viscosity (ref. 47) by

$$K = \mu \frac{NR}{8} \quad (9 \gamma - 5)$$

where N is the number of degrees of freedom of the molecules.

R is the universal gas constant.

γ is the ratio of specific heats.

For air this turns out to be

$$k = 9.22 \times 10^{-4} \quad \frac{T^{3/2}}{T + 260} \qquad \left(\frac{Btu - Ft}{hr\ Ft^2\ {}^oR}\right) \tag{2}$$

6.2.3 Trajectories and Flight Loads

The trajectories or mission profiles of high speed flight vehicles are established by solving the equations of motion of the vehicles. For example, in the case of a ground-to-air defense missile, the missile will be directed to achieve an intercept course with the attacking system. The forces acting on the missile are the thrust of the propulsion system, aerodynamic lift, aerodynamic drag and acceleration loads. Thus, knowing the initial position of the missile, its aerodynamic properties, and the thrust of its engine as well as the flight path of the attacking vehicle, a time-history of the position of the missile in space may be computed. In the process of this computation, all of the aerodynamic and acceleration loads on the radome as well as the heating rates at any instant of time can be computed.

The inverse of this problem may also be solved; i.e., given the time-history of the missile in space, the aerodynamic and acceleration loads as well as the heating rates can be computed if the aerodynamic properties of the missile are known.

a. Aerodynamic Loads: Probably the most useful aerodynamic tool for the evaluation of the aerodynamic forces on the nose radome of high-speed vehicles is Newtonian flow theory (refs. 46, 48, 49). Basically, the Newtonian concept is that the change in the normal component of momentum as a moving stream impinges upon a body is converted into an increment of pressure. Thus, the pressure coefficient on the surface of a body is

$$Cp' = K \cos^2 \eta \tag{3}$$

where η is the angle between the stream and the normal to the surface and K is dependent upon the type of body and fluid characteristics and for blunted bodies is given (ref. 48) by

$$K = Cp'_{stag} = \frac{\gamma + 3}{\gamma + 1} \left[1 - \frac{2}{\gamma + 3} \quad \frac{1}{M_\infty^2} \right] \tag{4}$$

where Cp'_{stag} is the stagnation point pressure coefficient

γ is ratio of specific heats

M_∞ is the free stream Mach No.

For pointed bodies, a slightly higher value appears to be more appropriate and the Newtonian value of 2 has been suggested (ref. 48). Reference 48 contains many charts that are useful for determining the total forces as well as load distributions on arbitrary bodies of revolution.

b. Aerodynamic Heating: The aerodynamic heating problem in the high-speed flight regime has been studied extensively over the past fifteen years and a veritable flood of reports, books, and articles have appeared. It is not the intent here to make a thorough survey but rather to indicate briefly some of the basic relationships that have been found to give reasonably reliable estimates of aerodynamic heating rates.

Basically, the heating input, q, to the surface of a high-speed flight vehicle can be expressed as

$$q = \underbrace{h\,(T_r - T_1)}_{\text{Convective aerodynamic heating}} - \underbrace{\varepsilon \quad \sigma \quad T_1^4}_{\text{radiant heat loss from the surface}} \tag{5}$$

and

$$T_r = \left[1 + (P_r)^n \; \frac{\gamma - 1}{2} \quad M_\infty{}^2 \right] T_\infty \tag{6}$$

where h = the film coefficient which will be discussed below.

T_1 = the temperature of the wall or surface.

ε = surface emissivity.

σ = Stephan-Boltzman constant.

γ = ratio of specific heats.

M_∞ = free stream Mach Number.

T_∞ = free stream or ambient temperature.

The Prandtl number, P_r, is defined as

$$P_r = \frac{Cp\ \mu}{R} \tag{7}$$

where Cp is the specific heat at constant pressure, μ is the viscosity, and K the thermal conductivity. For laminar flow, the exponent n is 1/2 while for turbulent flow the exponent is 1/3. The type of flow is strongly dependent on the local Reynolds number, R_e, defined as

$$R_e = \frac{\rho\ u\ x}{\mu} \tag{8}$$

where ρ is the local density

u is the local velocity

x if the coordinate along the surface of the structure (measured from the stagnation point)

The transitional Reynolds number between laminar and turbulent flow is on the order of 10^6 for a flat plate and $2x\ 10^6$ for a cone.

It has been shown (ref. 29,50) that if h_s is the heat transfer coefficient at the stagnation point, then the heat transfer coefficient at any other location can be expressed as $h = C_1 h_s$.

It has been shown (ref. 51) that for laminar flow, the heat transfer coefficient, h, is

$$h = \frac{0.763}{P_r\ 0.6}\ f\left(\frac{x}{D}\right) \left(\frac{\beta D}{U_\infty}\right)^{\frac{1}{2}} \left(\frac{\mu_\infty}{\rho_\infty U_\infty D}\right)^{\frac{1}{2}} \left(\frac{\rho_{\delta s}}{\rho}\right)^{\frac{1}{2}} \left(\frac{\mu_{\delta s}}{\mu_\infty}\right)^{\frac{1}{2}} \rho_\infty U_\infty C_\infty \tag{9}$$

where the subscript ∞ designates free stream or ambient conditions, and the subscript δ_s designates local stagnation conditions. The function, β, is determined from Newtonian theory as (ref. 51)

$$\beta = \frac{U_\infty}{D} \left\{ \frac{8\left[(\gamma - 1)\ M_\infty^2 + 2\right]}{(\gamma + 1)\ M_\infty^2} \left[1 + \frac{\gamma-1}{2}\ \frac{(\gamma-1)M_\infty^2 + 2}{2\ \gamma M_\infty^2 - (\gamma-1)}\right]^{\frac{1}{\gamma-1}} \right\}^{\frac{1}{2}} \tag{10}$$

where D is the diameter of the spherical nose. The function, $f\ (\frac{x}{D})$, is taken from reference and is given approximately by (ref. 50)

$$f\ (\frac{x}{D}) = 0.765 + 0.235 \cos 2.6\ (\frac{x}{D}) \qquad (11)$$

Equation 49 holds until the asymtotic value of h for a flat plate or cone is reached. This is given by (ref. 51)

$$h_{pL} = \frac{0.323}{P_r^{\ 2/3}} \quad \rho_\delta\ \mu_\delta\ Cp \qquad (12)$$

for laminar flow and by (ref. 51)

$$h_{pt} = \frac{0.030}{P_r^{\ 2/3}\ R_{e_\delta}^{\ 1/5}} \quad \rho_\delta\ \mu_\delta\ Cp$$

for turbulent flow. The values for flat plates can be used for cones by multiplying by the factor $\sqrt{3}$.

For turbulent flow over the spherical portion of the radome

$$h = \frac{0.042}{P_r^{\ 2/3}} \left(\frac{\beta\ D}{U_\infty}\right)^{4/5} \left(\frac{\mu_\infty}{\rho_\infty\ U_\infty\ D}\right)^{1/5} \left(\frac{\rho_\delta}{\mu_\infty}\right)^{4/5} \left(\frac{\mu_\delta}{M_\infty}\right)^{1/5} (\frac{x}{D})^{3/5}\ \rho_\infty\ U_\infty\ Cp \qquad (13)$$

The ratios $\frac{\rho_\delta}{\rho_\infty}$, $\frac{\mu_\delta}{\mu_\infty}$, and β are evaluated by computing the pressure ratio from Newtonian theory and isentropic expansion from the stagnation point.

We note that the ambient properties of the flow are determined by specifying the altitude of the vehicle and the atmospheric properties. Thus, if the altitude and velocity, U_∞, of the vehicle areknown or specified as a function of time, and the geometry of the radome is known, the aerodynamic forces and heat transfer coefficients can be computed as a function of time anywhere on the surface.

6.3 Structural Analysis

The most important stresses in the radomes of high-speed flight vehicles are due to the thermal gradients within the structure. Therefore, most of the emphasis in this section will be placed on the thermal stress problem.

The first step in a thermal stress analysis is to determine the temperature distribution in the radome as a function of time. For nearly all practical cases of radome heating, the heat transfer coefficient, h, and recovery temperature, T_r, will not be a simple function of time. Therefore, a numerical solution of the heat flow and temperature distribution in the radome will be required.

Again there has been a large volume of reports and papers on the formulation and solution of heat flow problems (for example, refs. 52-55). Two methods which have been found to be quite useful will be considered herein. The first of these is known as Dusinberre's method (ref. 53) which essentially consists of dividing the wall into a finite number of slabs or layers and finding the time variation of the heat balance in each one. The second is known as Hill's method (ref. 52) and involves the super position of a series of triangular heat pulses which are combined to represent the heat input to the radom.

Figure 5 is a typical radome shell and describes the coordinate system used as well as the subdivision of the wall into several layers. The outer surface of the radome has a known time-history of heat input while the inner surface is assumed to be insulated. Applying Dusinberre's method to the outer surface, there is obtained at time mδ

$$T_{1,m} = F_{aw,1}\, T_{r,m-1} + F_{1,1} T_{1,m-r} + F_{2,1}\, T_{2,m-1} - \epsilon\sigma\, T_{1,m-1}^{4} \tag{14}$$

where
$$F_{aw} = h\,\frac{\Delta b}{K}\,\frac{Z}{P} \tag{15}$$

$$F_{2,1} = \frac{Z}{P} \tag{16}$$

$$F_{1,1} = 1 - F_{aw,1} - F_{2,1} \tag{17}$$

The subscripts used are defined as follows:

$T_{n,m}$

m — Time interval

n — Distance interval

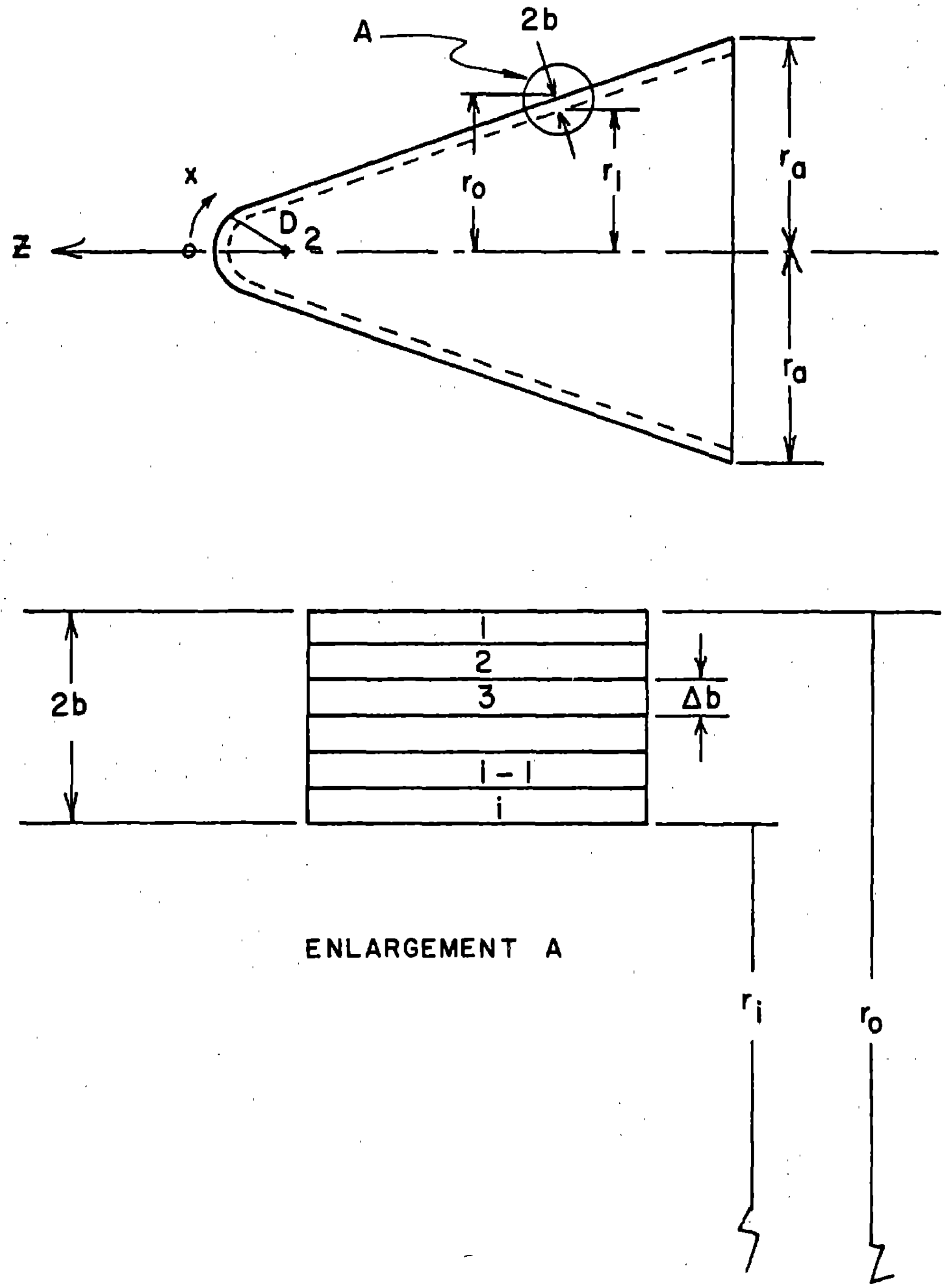

Figure 5 . Typical Ceramic Radome Geometry

and $\Delta b = \dfrac{2\ b}{i-1}$

P is some value such that

$$P \geqslant 2+2\ \frac{h\Delta b}{R} \tag{18}$$

The value of P dictates the time interval used in the step-by-step solution as given by

$$\delta = \frac{c\rho\ (\Delta b)^2}{k\ P} \tag{19}$$

and c is the specific heat of the wall material.

ρ is the density of the wall material.

k is the thermal conductivity of the wall material.

The inner surface temperature is given by

$$T_{i,m} = F_{i-1,i}\ T_{i-1,m-1} + F_{i,i}\ T_{i,m-1} \tag{20}$$

and $F_{i-1,i} = \dfrac{2}{P}$

$$F_{i,i} = 1 - F_{i-1,i}$$

Finally, the intermediate wall temperatures are given by

$$T_{n,m} = 1/2\ (T_{n-1,\ m-1} + T_{n+1,m-1}) \tag{21}$$

The practical use of these equations requires the use of a digital computer.

The outer surface temperature at time $m\delta$ from Hill's method is

$$T_{1,m} = \frac{(H\ T_r)_m + (H\ T_r - HT_1)_{m-1} - M_2 T_{1,\ m-1} - M_3 T_{1,\ m-2}\ \cdots - M_m\ T_{1,1} - R_m - R_{m-1}}{M_1 + H_m} \tag{22}$$

where $H = \dfrac{h\delta\ \pi^2}{16G}$ (23)

$$R = \frac{E\ \sigma T_1^{\,4}\ \ \pi^2}{16\ G} \tag{24}$$

$$G = \rho c(2b) \tag{25}$$

where M_i are memory coefficients which are tabulated in reference 52 as a function of $\dfrac{R\ \delta}{\rho c(26)^2}$. The inner surface temperature is given by

$$T_{i,m} = T_{1,m} - (\theta_1\ T_{1,m} + \theta_2 T_{1,m}\ {-1} + \ldots + \theta m\ T_{1,1}) \tag{26}$$

and the values of θ_i are also tabulated in ref. 52. Intermediate temperatures through the wall can also be obtained but the amount of computation required is very large and it is therefore not convenient. However, in order to obtain the thermal stresses, it is necessary to know the distribution of the temperatures in the wall. Assume that the temperature at any point in the wall can be expressed as

$$T = T_i + (T_1 - T_i)\ \left(\frac{y + b}{2b}\right) \tag{27}$$

The average temperature in the wall, T_{ave}, is given by

$$T_{ave} = \frac{1}{2b} \int_{-b}^{b} T\ dy$$

Integrating, there is obtained

$$T_{ave} = Ti + \frac{T_1 - T_i}{j + 1}$$

But, the average temperature in the wall can also be obtained from the

heat input. Thus, at any time $t = m\delta$

$$T_{ave} = \frac{1}{2\delta\rho c} \int_{o}^{m\delta} h\,(T_r - T_1)\,dt$$

Therefore, the value of j at any time interval can be estimated quite readily from

$$j = \frac{T_1 - T_i}{\frac{1}{2bc\rho} \int^{m\delta} h(T_r - T)\,dt - T_i} - 1 \tag{28}$$

After the temperature distribution has been obtained, the next step is to compute the thermal stresses. This is done by approximating the shell by a series of cylindrical shells. From reference 56 the equations for the stresses in a cylindrical shell with an inner radius of r-b and an outer radius of r+b can be express as

$$\sigma_\theta = \frac{r^2 + r_i^2}{r^2(r_o^2 - r_i^2)} \int_{r_i}^{ro} \frac{\alpha\ ET}{1-v}\,rdr + \frac{1}{r^2} \int_{r_i}^{r} \frac{\alpha\ ET}{1-v}\,rdr - \frac{\alpha\ ET}{1-v} \tag{29}$$

$$\sigma_z = \frac{2}{r_o^2 - r_i^2} \int_{r_i}^{r_o} \frac{v\alpha\ ET}{1-v}\,rdr - \frac{\alpha\ ET}{1-v} \tag{30}$$

When the thickness of the shell is small in comparison to the radius ($\frac{r}{2b} \gg 1$) then these equations reduce to the flat plate (ref. 56)

$$\sigma_\theta = \sigma_z = \frac{\alpha\ E}{1-v} \left[T - \frac{1}{2b} \int_{-b}^{b} tdy - 3\,\frac{y}{2b^3} \int_{-b}^{b} y\ Tdy \right] \tag{31}$$

In addition to the stresses from the thermal gradient through the wall, there will be stresses that result in the attachment of the radome to the vehicle structure. This is illustrated schematically in figure 6.

In the vicinity of the attachment, the recovery temperature, T_r, will be the same for both the radome and the structure to which it is attached. However, in general, the temperatures of the two structures will not be the same nor will the resultant thermal expansion. This is because the thermal diffusivities and thermal expansion coefficients are different. This condition is shown in figure 7. When the two sections are joined, the two deformations must be made compatible, which implies additional stresses. The design will generally be carried out so that the mismatch in the slope does not introduce additional stresses (i.e., a pin-jointed boundary condition). Assuming that the radome and the vehicle structure started out at the same temperature, then

$$\Delta r = \delta_r - \delta_m = (\alpha_r T_{r_{ave}} - \alpha_m T_{m_{ave}}) \tag{32}$$

The radial displacement from a uniformly distributed radial edge load, V o, applied to a cylindrical shell is (ref. 56)

$$= \frac{V\,o}{z\,\bar{D}\,\lambda} \tag{33}$$

where $\bar{D} = \dfrac{z\,Eb^3}{3(1-v^2)}$

$\lambda = \sqrt[4]{\dfrac{3\,(1-v^2)}{4\,ra^2\,b^2}}$

v = Poisson's ratio

Thus, the edge load required to match the radome to the vehicle shell is

$$V\,o = 2\,\Delta\,r\,\frac{1}{\left(\dfrac{1}{\bar{D}r\,\lambda\,r} + \dfrac{1}{\bar{D}m.\,\lambda\,m}\right)} \tag{34}$$

The bending moment in the radome is then given as (ref. 56)

$$M = \frac{1}{\lambda_r}\;Vo\;\bar{e}^{-\lambda\,r\,z}\,\sin\lambda r\,z \tag{35}$$

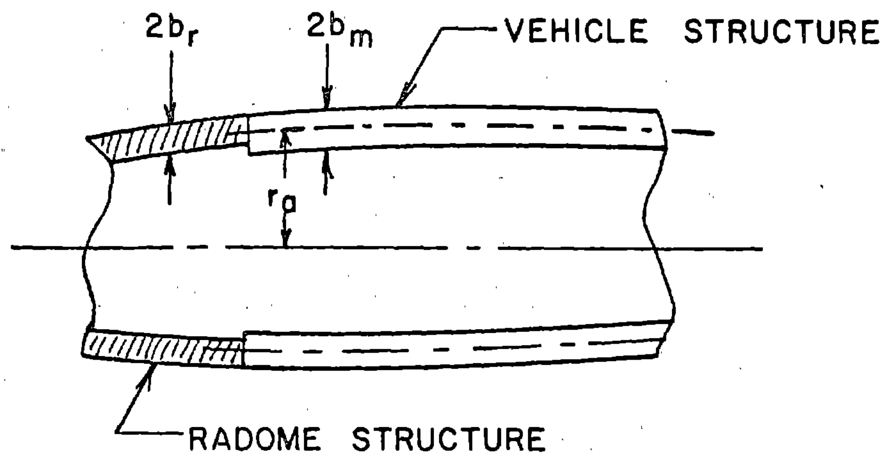

Figure 6. Junction of Radome with Missile

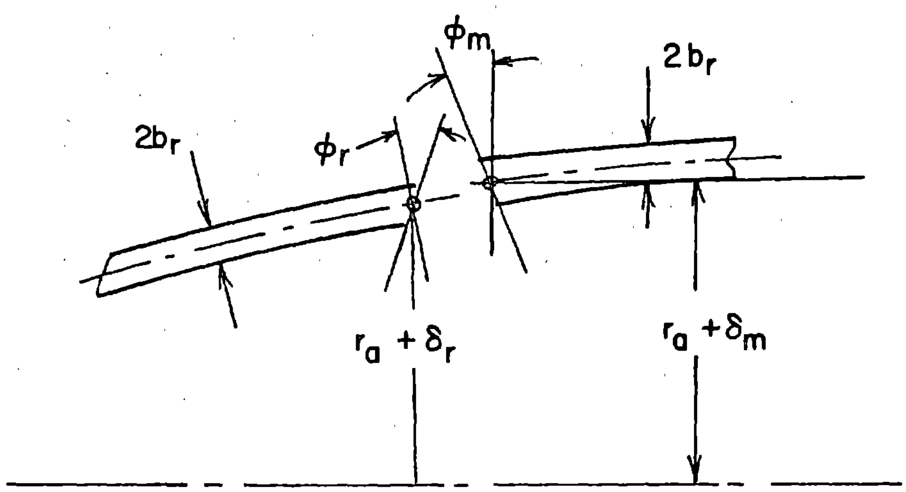

Figure 7. Thermal Deflection at Radome Joint

6.4 Illustrative Example

For an illustrative example, a small air-to-air missile will be considered. It is assumed that the missile is released from an aircraft operating at 30,000 ft. with a flight Mach No. of 1.2. The missile is launched at an angle of 30 degrees from the horizon. The missile parameters are assumed as follows:

Launch weight, W_L	= 510 lbs
Thrust, T	= 3600 lbs
Burning time, t_b	= 20 sec.
Propellant weight, W_p	= 360 lbs
Average drag coefficient, $\bar{C}_D$	= 0.3
Reference cross-sectional area, $\bar{S}$	= 0.90 sq. ft.

These parameters along with atmospheric data discussed above can be used to provide the input for the equation of motion along the flight path, i.e.,

$$T - \frac{\bar{C}_D \bar{S}}{2} \rho_\infty \; U_\infty^2 - \frac{1}{2}\left(W_L - W_p \frac{t}{t_b}\right) = \frac{1}{g}\left(W_L - W_p \frac{t}{t_b}\right) \frac{dU_\infty}{dt}$$

where ρ_∞ is the density, which is a function of altitude, and g is the acceleration of gravity. This equation was solved numerically and the resulting trajectory is shown in figure 8 as plots of Mach No. and altitude versus time. It should be noted that this trajectory calculation is simplified in that an average drag coefficient is assumed rather than allowing it to vary with Mach No. Although a more exact calculation would normally be used in a final design, this example illustrates the general procedure.

The radome was assumed to have a nose radius of 1.5 inches, a base diameter of 12 inches and a fineness ratio of 1.5. Using the trajectory plots of figure 8 and equations (6) and (9), the recovery temperature, T_r, and the stagnation heat transfer coefficient, h_s, were computed as a function of time as shown in figure 9. For a final design, the heat transfer coefficient would be computed at several locations along the radome.

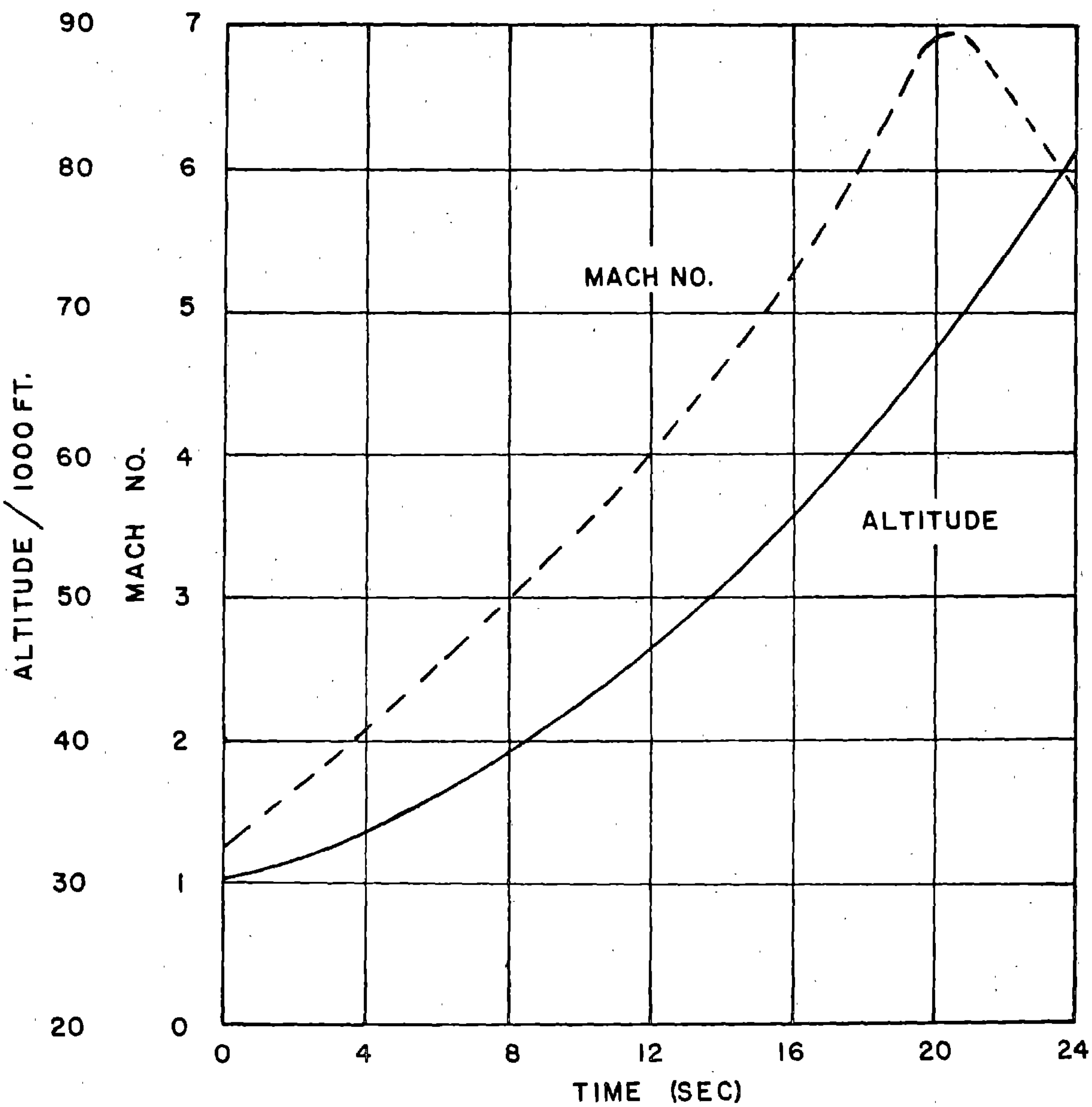

Figure 8. Missile Trajectory

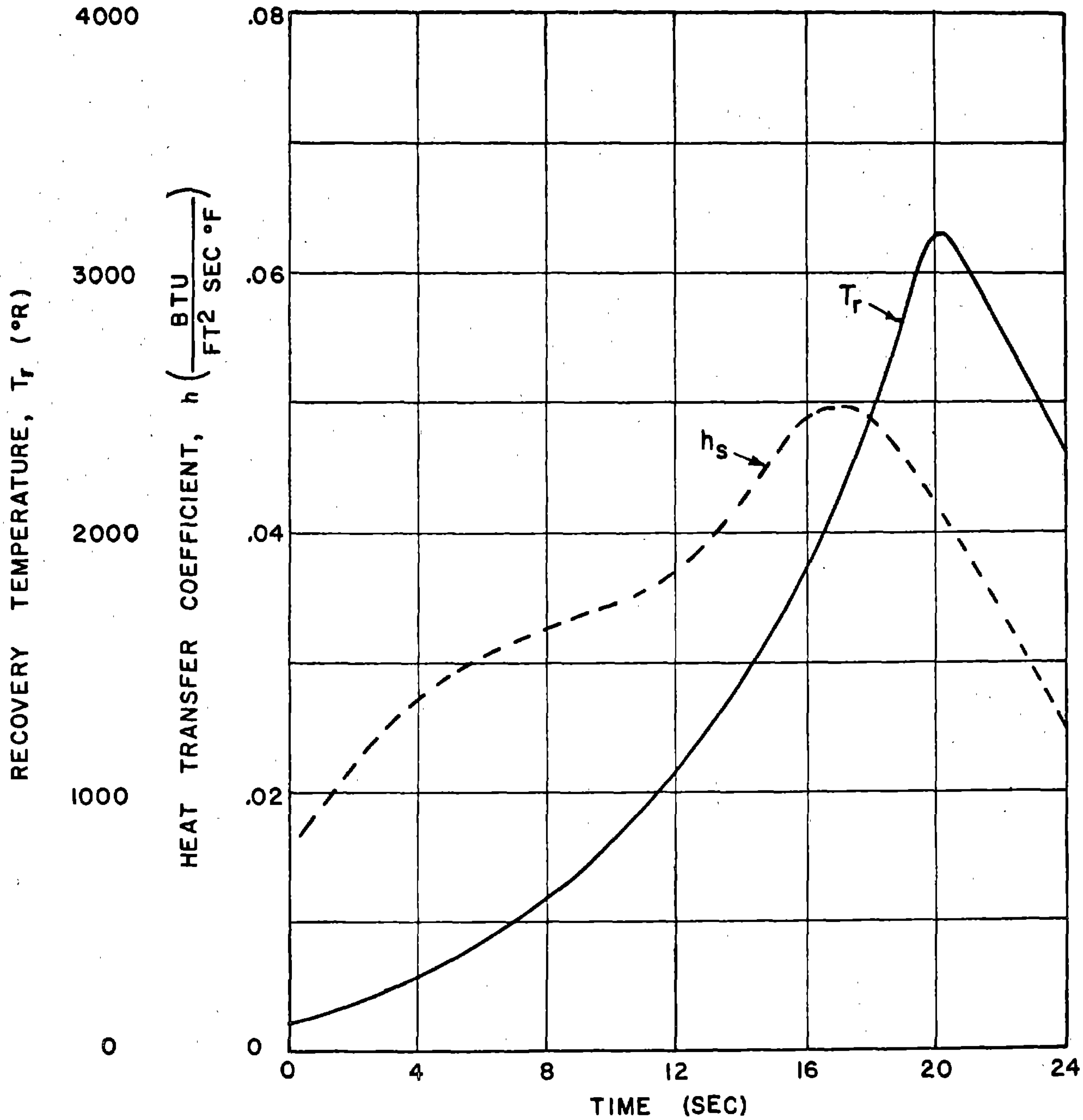

Figure 9. Recovery Temperature and Heat Transfer Coefficient versus Time

The next step in the design process is the determination of the temperature distribution and temperature stresses in the radome. For this illustration, an X-band alumina radome was selected having a wall thickness of 2b = 0.18 inch. The inner and outer surface temperatures were computed as a function of time using equations (22) and (26) along with the tables in reference 52. The following parameters were used for this calculation:

Thermal conductivity, k	$= 10.7 \dfrac{\text{Btu - Ft}}{\text{ft}^2 \ \text{hr} \ {}^\circ\text{F}}$
Specific heat, C	$= 0.16$ Btu/lb $^\circ$F
Density, ρ	$= 240$ lbs/ft^3
Wall thickness, 2b	$= 0.015$ ft.

A plot of the inner surface and outer surface temperatures is given in figure 10. The largest temperature difference, $T = 186^\circ$F, occurs at t = 18 seconds and therefore causes the maximum tensile stress. As described above, the average temperature in the wall is found by dividing the total heat input by heat capacity. The total heat into the structure can also be computed conveniently by Hill's method. The average heat input during any interval is given by (ref. 52)

$$q = \frac{8G}{\pi^2 \delta} \quad (M_1 T_m + M_2 T_{m-1} + \dots + M_m \ T_1)$$

where the symbols are the same as for equation (22). The total heat into the structure at 18 seconds was found to be 482 Btu per ft^2. Thus, the average temperature at 18 seconds is

$$= \frac{482}{(240)\ (0.16)\ (0.015)} = 838^\circ\text{F}$$

The exponent j is found from equation (28)

$$j = \frac{T_1 - T_i}{T_{ave} - T_i}$$

$$j = \frac{965 - 778}{838 - 778} - 1 \cong 2$$

so that the temperature distribution is

$$T = 778 + 186 \ \frac{y + 0.09}{0.18}^{\,2}$$

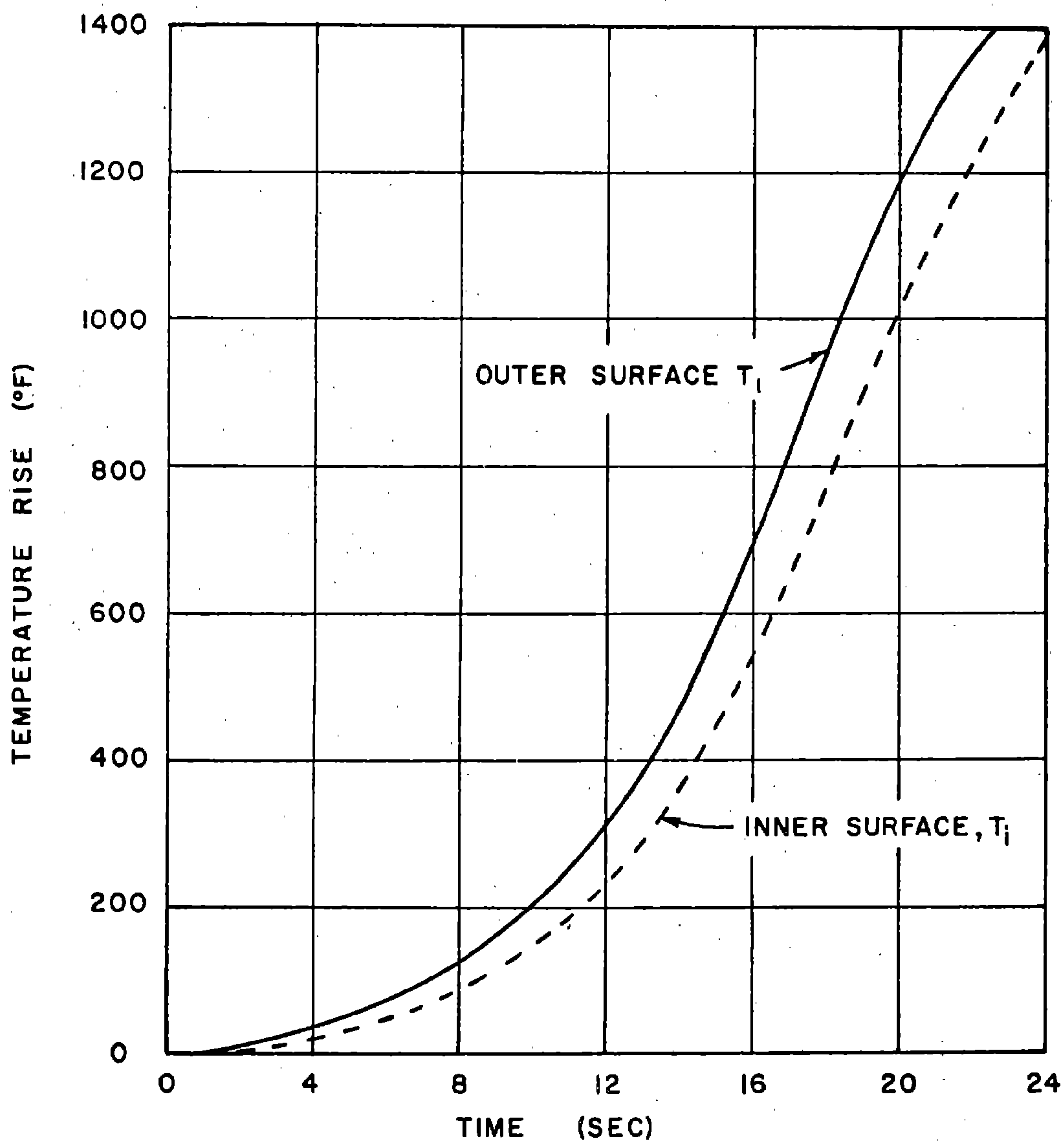

Figure 10 . Temperature Rise of Radome versus Time

Substituting this into equation (31) and integrating gives for the maximum tensile stress at $y = -\sigma$

$$\sigma_\theta = \sigma_z = 0.375 \frac{E\alpha\,(T_1 - T_i)}{1 - \nu}$$

and with

$$E = 50 \times 10^6 \text{ psi}$$

$$\alpha = 4.3 \times 10^{-6}$$

$$\nu = 0.25$$

the stress becomes

$$\sigma_\theta = \sigma_z = \frac{0.375\,(50)\,(4.3)\,(186)}{0.75} = 20{,}000 \text{ psi}$$

which is within the strength capability of the alumina material (i.e., σ allowable - 29,240 psi).

The attachment of the radome to the missile frame will now be examined. Equation (32) gives the difference in thermal displacement between the radome and the missile structure. Assume that the heat input in the area of the attachment is 80 percent of that at the stagnation at t = 18 seconds. Thus, $Q = 482\,(0.80) = 385 \text{ Btu/ft}^2$. If the same amount of heat is assumed to go into both the missile and the radome structure, equation (32) can be rewritten as

$$\Delta r = \alpha_r r_a \frac{385}{(0.015)\,(240)\,(0.16)} \left(1 - \frac{\alpha\, m}{\alpha\, r} \quad \frac{C_r\, b_r\, \rho_r}{C_m\, b_m\, \rho_m}\right)$$

and with $r_a = 6$ in. and $\alpha_r = 4.3\text{x}10^{-6}$

$$= 0.0172 \left(1 - \frac{\alpha\, m}{C_m\, \rho_m\, b_m} \quad \text{x } 6.7\text{x}10^4\right)$$

If the missile structure were made from 0.10 inch thick high-temperature steel, then

$$\frac{\alpha m}{C_m\, b_m\, \rho_m} = \frac{10\text{x}10^{-6}}{(0.10)\,(496)\,(0.00415)} = 4.42\text{x}10^{-5}$$

and

$$\Delta_r = 0.0172\ (1 - 3.96) = 0.051 \text{ inch}$$

Equation (34) gives the distributed radial shear load. Thus, with

$$\bar{D}r = \frac{2E_r\ b_r3}{3(1 - \nu_r2)} = \frac{2(50)\ (10^6)\ (0.09)^3}{3(1 - 0.0625)} = 25900$$

$$D_m = \frac{2E_m\ b_m2}{3(1 - \nu_m^2)} = \frac{2(23)\ (10^6)\ (0.05)^3}{3(1 - 0.0625)} = 2040$$

$$\lambda_r = \sqrt[4]{\frac{3(1 - \nu_r^2)}{4\ r_a^2\ b_r^2}} = 1.245$$

$$\lambda_m = \sqrt[4]{\frac{3(1 - \nu_m^2)}{4\ r_a\ b_m^2}} = 1.675$$

V_o becomes

$$V_o = 2(0.051)\ \frac{1}{\frac{1}{25900} + \frac{1}{2040}}$$

$$V_o = \frac{0.102}{53} \times 10^5 = 192.5 \text{ lbs/in.}$$

The bending moment in the radome is given by equation (35)

$$M = 155\ \bar{c}^{\ -1.245z} \sin 1.245\ z$$

The maximum moment will occur at

$$z = \frac{\pi}{4(1.245)} = 0.63 \text{ inch}$$

and is

$$M_{max} = 155\,\bar{e}^{\,-pi\ \pi_4\ II_4} \sin\frac{\pi}{4} = 50 \text{ in lbs/in.}$$

which will give a stress of

$$\sigma = \frac{6M}{(2b)^2} = \frac{6(50)}{(0.18)^2} = 9250 \text{ psi}$$

since this combines with the thermal stress caused by the temperature distribution through the wall, the attachment is the critical area.

6.5 Discussion

Two of the most important aspects in the structural design of radomes fabricated from nonmetallic inorganic refractory materials have been examined in the illustrative problem. The first of these is the high thermal stresses that occur at high temperatures. The requirement for higher speed missiles and other flight vehicles will cause this problem to become more severe. It was noted that for the particular missile and mission selected, the alumina radome was found to be satisfactory. However, had the burning time been longer, the thermal stresses at temperature would have exceeded the allowable strength value for the material. One approach that appears to offer promise for higher speed longer duration vehicles is that of coating the radome with an ablative material. This approach was examined in reference 57 by test and by analysis and it was found that an ablative coating could be designed to extend considerably the duration of high-speed flight.

In any application of ceramic radomes to high-speed flight vehicles, the relative merits of the use of ablative coatings with the various ceramic radomes must be examined in detail. The least expensive way to make this type of survey is analytically, although material tests will always be required to provide adequate input data. The general engineering approach described above will serve this purpose reasonably well. However, in the interest of obtaining results quickly and inexpensively, it is recommended that the radome manufacturers have the appropriate equations programed for high-speed digital computers.

The second important aspect is that of the attachment of the radome to the vehicle structure. This is an area where the details of the design are very critical. The two points to consider in this problem are (1) the relative radial expansion between the vehicle and the radome

and (2) the radial shear load produced by the difference in expansion. For a constant heat input, it was seen that the difference in radial expansion could be expressed as

$$\Delta r = \alpha_r T_{rave} (1 - A)$$

$$A = \frac{\alpha m}{\alpha r} \quad \frac{C_r b_r \rho_r}{C_m b_m \rho_m}$$

To minimize Δr, it is necessary to make the ratio A as near to unity as possible. This must be done by considering both material properties and the geometric properties as typified by the equivalent shell thickness of the vehicle, i.e., 2 b_m. One interesting approach that might be explored is the use of some sort of heat shield in the area of attachment. It is conceivable that this shielding might be distributed in such a way as to reduce considerably the thermal mismatch.

Another approach that can be used to reduce the stresses is to design the attachment so that the forces generated by the mismatch are kept small in magnitude. This is done by making the term $\bar{D}m \; \lambda m$ in equation (34), which represents the attachment stiffness, as small as possible. Obviously, there must also be a compromise here because the attachment must also meet the strength requirements. Finally, the design of the attachment should be such as to reduce to a minimum its bending rigidity, or clamping action on the radome.

These general principles provide a guideline to the approach and the important parameters of nonmetallic inorganic refractory material radome design. The solution of the problem requires, however, a careful study of each individual case by the structural designer.

7. TEST METHODS

The first step in organizing a survey of the existing data on inorganic refractory materials is to investigate the theories and methods used to evaluate the pertinent data. It becomes imperative that one survey not only the existing data, but also the method used to generate the data. Once the methods have been approved as satisfactory, one must compare the data of the various methods to determine the most reliable results.

7.1 Mechanical Measurements

Currently available methods for accurate mechanical measurements were surveyed under Air Force contract No. AF33(657)-8064 by the Engineering Experiment Station, Ohio State University. Theoretical basis of tests, practical limitations and present practices are discussed as they pertain to tensile strength, compressive strength, flexural strength, modulus of elasticity, modulus of rigidity, Poisson's ratio and termal shock resistance.

7.2 Thermal Measurements

Current methods for measuring thermal properties pertinent to this report are being covered in detail in the supplement to the WADC-TR-57-67, Techniques for Airborne Radome Design, by McGraw Hill Publishing Co.; therefore, the methods used to generate the thermal properties will only be mentioned whenever they are known.

Detailed thermal and mechanical properties of single oxides and mixed oxides can be found in the report prepared by Battelle Memorial Institute under Air Force Contract No. AF33(657)-8326; this report also contains information on measuring methods.

Since it was not the major goal of this report to investigate thoroughly the techniques and practices of mechanical and thermal measurements, the investigators of this work (on the advice of the contracting officer) merely reference AF33(657)-8064 and AF33(657)-8326 for a working knowledge of the state of the art.

7.3 Electrical Measurements

The precise design of a radome must necessarily be predicated upon a detailed knowledge of the dielectric characteristics of the material selected for use. The lack of such information becomes apparent after any series of boresight tests. Future emphasis upon aerospace applications has increased the overall complexity of the problem through the addition of environmental extremes.

During the early stages of radome development, many methods for measuring dielectric constant and loss tangent were devised. However, there was much disagreement among the many investigators. Because of the large amount of data published during these early days one must be extremely cautious to discriminate between the good and the bad. For this reason it was felt that a more detailed outline than the existing outline[58] in ARTC-4 should be presented to substantiate ARTC-4 and make this report more meaningful.

This report will show that accurate measurements of dielectric constant and loss tangent at microwave frequencies can be performed by several proven methods, each of which has its own merit. Dielectric constant and loss tangent data on refractory materials at elevated temperatures are included and compared in the Appendix to this report.

7.3.1 Resonant-Cavity Technique (Variable-Frequency)

Recent measurements have been made[6] by forming a cavity around the sample being tested. The samples were right cylinders, 0.999 ± 0.001 inch in diameter, with thicknesses between 5/8 and 7/8 inch, and plane and parallel to 0.005 inch.

For the frequency-variation resonant-cavity method, samples were formed into dielectric-filled resonators by the application of metallic coatings. Figure 11 shows the experimental equipment used for this measurement. From ambient temperature to 850°C, silver paint was used. Platinum paint was used to extend the temperature range to 1200°C. In order to attain 1400°C, it was necessary to go to 0.0015-inch thick platinum foil.

Using a right cylinder with the diameter greater than the height, the lowest frequency of resonance is for the TM_{010} mode:

$$\lambda = 1.30637\, D\, K$$

and the Q of the cavity with lossless dielectric is:

$$Q_w = \frac{10^4 \sqrt{\lambda/S}}{1 + \frac{0.384\,\lambda}{h}}$$

where λ = free space wavelength in cm at resonant frequency

D = diameter in cm

h = height in cm

S = resistivity of metal walls relative to copper.

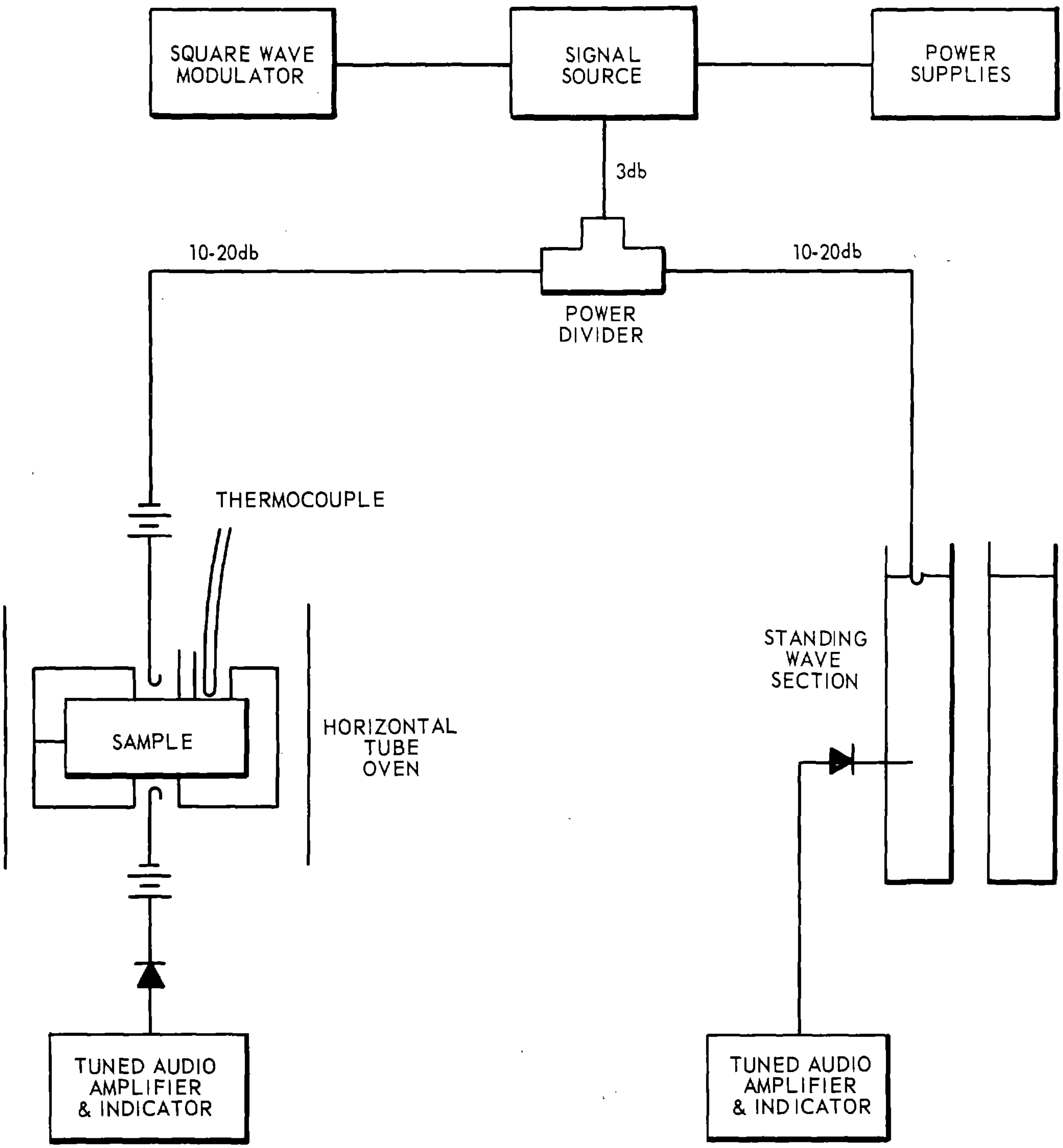

Figure 11 Block Diagram of Equipment Used in Variable-Frequency Resonant-Cavity Technique for Determination of Dielectric Constants

The total losses are measured by width, $\Delta\lambda$, of the resonance curve between half-maximum power points. The difference between the apparent loss tangent of the cavity and $1/Q_w$ is the dielectric loss tangent.

$$\tan\delta = \frac{\Delta\lambda}{\lambda} \; \frac{1}{Q_w}$$

All the measurements given in this report were made using the TE_{111} mode, the next lowest frequency mode for which

$$\lambda = \frac{\sqrt{K}}{\left(\frac{0.3434725}{D^2} + \frac{0.25}{h^2}\right)^2}$$

and

$$Q_w = \frac{1.31 \times 10^4 n}{\sqrt{\lambda S}} \left[\frac{2.39\ h^2 + 1.730\ D^2}{3.39\ \frac{h^3}{D} + 0.73\ Dh + 1.73\ D^2}\right]$$

7.3.2 Resonant-Cavity Technique (Variable - Length)

The resonant cavity technique is particularly suitable for measuring dielectric constant and loss tangent of medium and low loss dielectric materials in the 8.0 Gc to 40.0 Gc range.

Two of the more widely used cavities are those which employ disc-shaped or rod-shaped samples. Other variations commonly made are to employ either transmission coupling or reflection coupling to a right circular cylinder operating in the TE_{01n} mode. The cylinder is excited into resonance by varying its length or adjusting the input signal frequency.

A variable-length cylindrical transmission cavity (shown in figure 12) operating in the TE_{01n} mode has been used for this purpose. A circular sample slightly smaller in diameter than the cavity is prepared from the material to be measured. Sample thickness is usually between 0.1 inch and 0.2 inch, depending on the estimated dielectric constant of the material, and the sample must be plane and parallel within about 0.001 inch for good results. Figure 13 shows the position of the variable-length resonant cavity in the system.

For a specific frequency, the change in length required to return the cavity to resonance after inserting the sample is a measure of the dielectric constant of the sample. The change in cavity "Q" produced by the presence of the sample can be used to calculate its loss tangent.

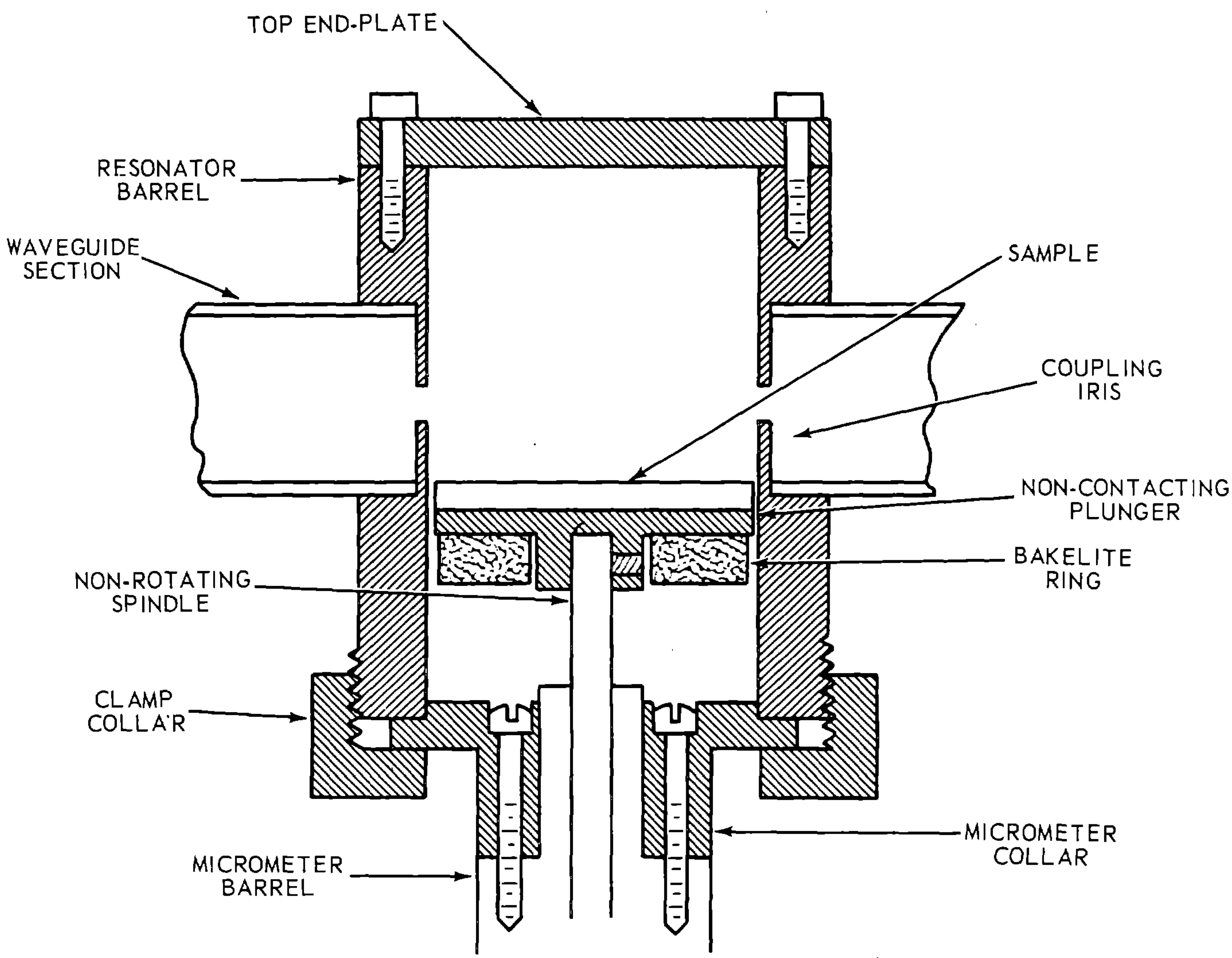

Figure 12 A Variable-Length Cylindrical Transmission Cavity

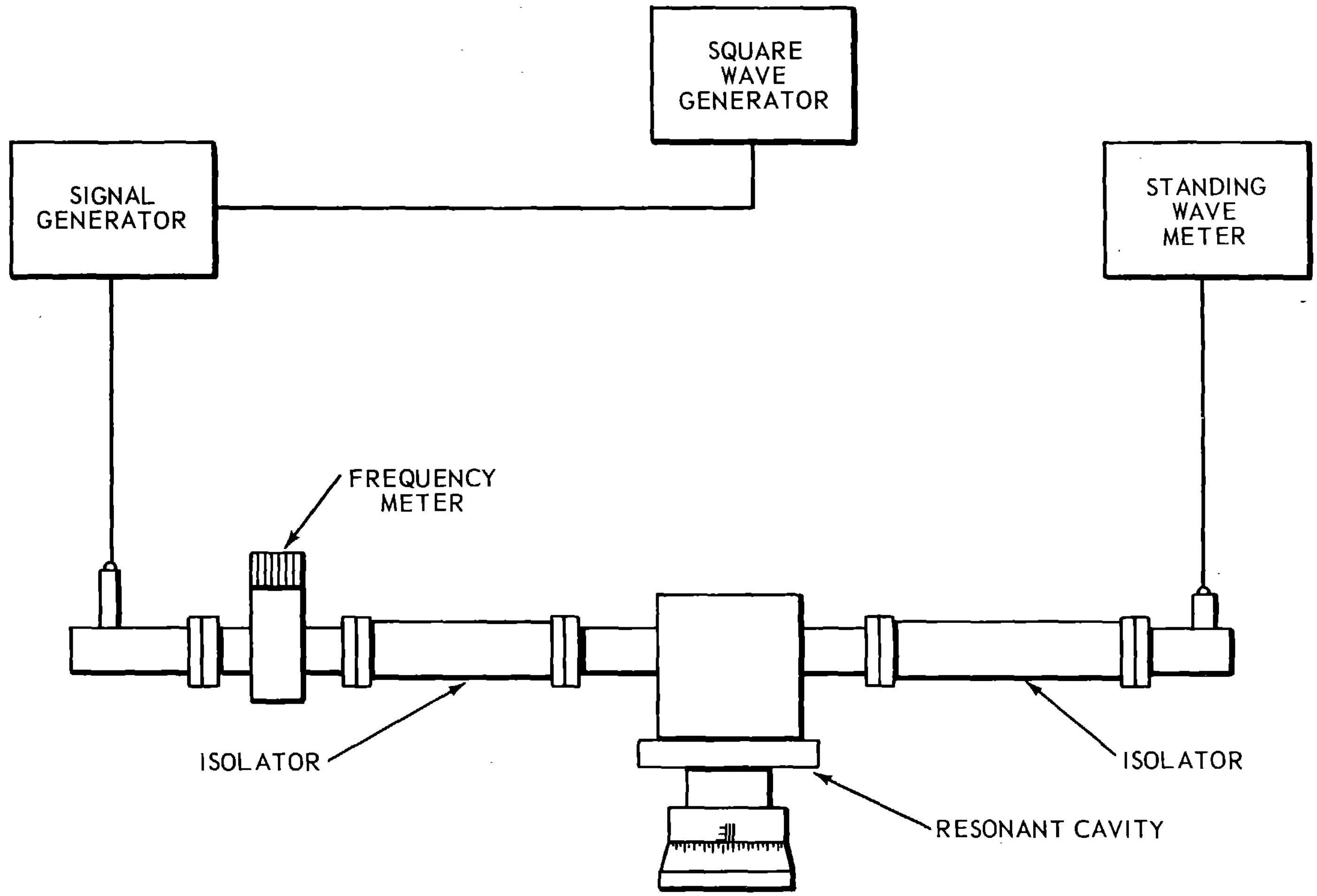

Figure 13 Block Diagram Demonstrating the Position of the Variable-Length Resonant Cavity in the System

In the system shown in figure 13 the empty cavity is tuned to a condition of resonance by moving the plunger to the TE_{013} mode. The cavity is then tuned to the TE_{012} mode. The linear distance between the two modes represents one half of the wavelength in the cavity, $\lambda_g/2$, from which λ_g is obtained. Resonance positions are located by noting maximum power readings on the Standing Wave Ratio Meter. After repeating this procedure with the sample in the cavity, it can be shown by the following relation that the altered resonant length by the presence of the sample is a measure of the dielectric constant, K.

$$\frac{-\tan \beta_1 b}{\beta_1} = \frac{\tan \beta_0 (\ell_0 - b)}{\beta_0}$$

where ℓ_0 = empty cavity resonant length,

b = sample thickness,

and

$$\beta_0 = \frac{2\pi}{\lambda_g}$$

The dielectric constant, K, may then be calculated from the expression

$$K = \frac{\beta_1^2 + k^2}{\beta_0^2 + k^2}$$

where

k = transverse phase constant.

To determine the loss tangent one must measure the cavity, Q, with and without the sample present. This is performed by measuring the 3-db width, $\Delta\ell$, or half-power points. The cavity, Q, is then determined by:

$$Q = \frac{\beta_0^2 + k^2}{\beta_0} \left(\frac{\ell}{\Delta\ell} \right)$$

where

ℓ = the resonant length of the cavity.

The loss tangent, tan δ, is calculated by:

$$\tan\delta = A \left(\frac{1}{Q} - \frac{1}{Q_0} \right.$$

where

Q_0 = Q of the empty cavity,

Q = Q of the loaded cavity.

The constant A, introduced for reasons of simplicity, incorporates the constants such as power loss at the metal boundaries, skin depth, or depth of current penetration which are peculiar to air-filled cavities.

7.3.3 Shorted-Line Technique (Rectangular Waveguide)

Standing-wave measurements in the transmission line in front of solid dielectrics provide rapid evaluation of dielectric constant and loss tangent. The method consists of reflecting the wave at normal incidence from a sample placed against a perfectly reflecting surface. This reflection process sets up standing waves in the space region in front of the specimen as a result of the superposition of the incident and reflected waves. An electric field is maintained at right angles to the direction of propagation of the wave; and is, therefore, a transverse electric (TE) wave.

The separation of the first minimum from the face of the sample will depend on the wavelength of the wave in the sample and the sample thickness, since the first minimum will be an integral number of half-waves from the reflecting surface behind the sample. Insertion of the dielectric sample shifts the minimum of the standing wave toward the shorted end of the guide. Figure 14 illustrates this shorting of the wavelength and the resultant shift of the standing wave. The separation of the first minimum of the standing wave from the interior surface of the specimen is a measure of dielectric constant. Experimentally, this data may be obtained with the aid of a movable reflector.[58]

Figure 15 shows an arrangement of the apparatus used in making the measurements for the determination of the dielectric properties by the short-circuit-line method. A dielectric sample placed adjacent to the short circuit causes: (1) a shift in position of the standing wave toward the short circuit; and (2) broadening of the standing wave nodes. For materials having loss tangent values less than 0.1000, the dielectric constant and loss tangent can be evaluated independently from values of the shift $(X_2 - X_1)$ and the associated broadening $(\Delta X_2 - \Delta X_1)$, respectively. An arbitrarily selected node in the voltage-standing-wave form may be located by use of the slotted line. Use is made of the existing relationship between X_0, the calculated distance from the sample face to the first minimum, and the uncorrected dielectric constant expressible parametrically by the equation:

$$k = (1 - p)\, q^2 + p$$

where

$$q = \frac{\tan 2\pi d_s\, (X_o/\lambda_g)}{\tan 2\pi x_o\, (d_s/\lambda_g)}$$

and

$$p = (\lambda/\lambda_c)^2$$

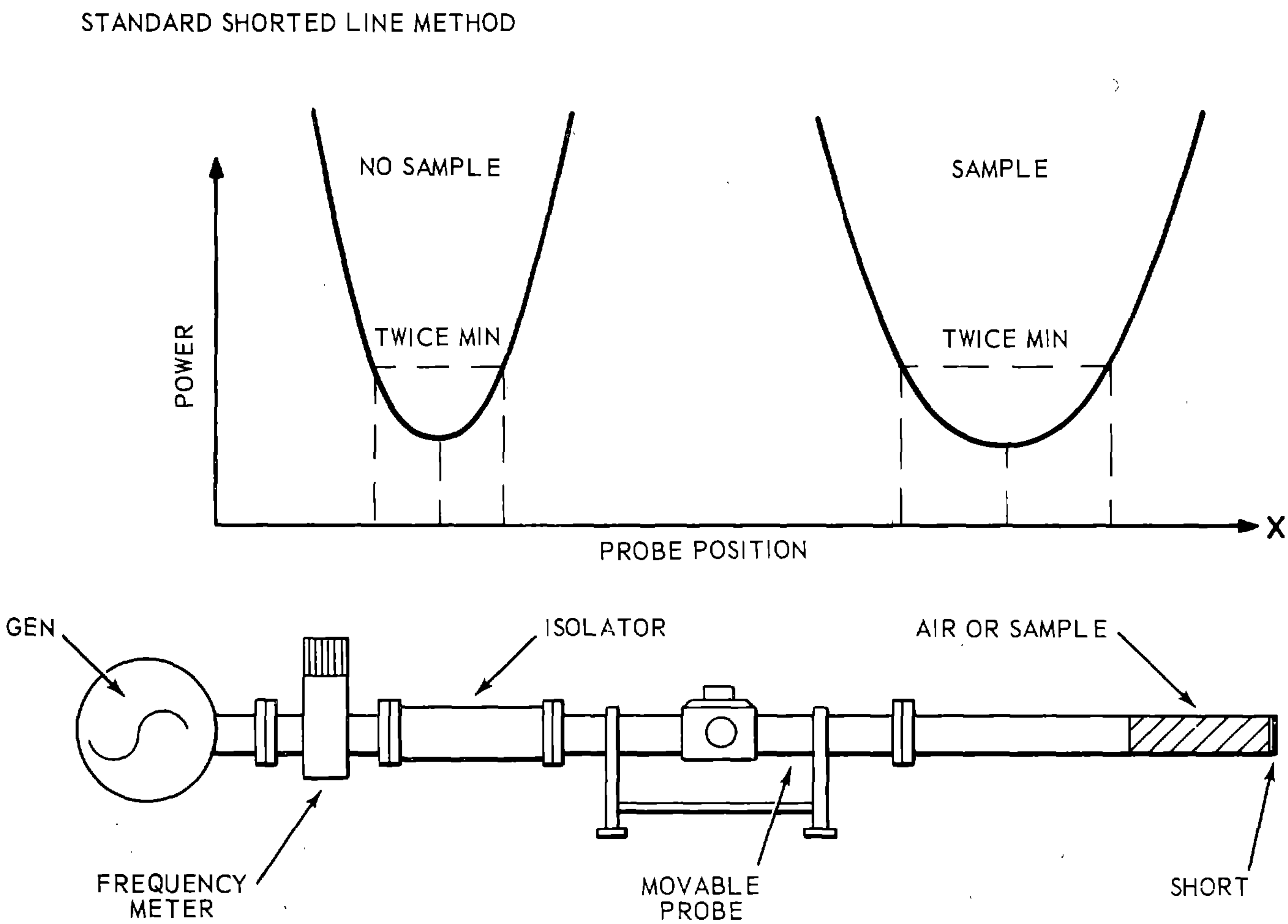

Figure 14 Pictorial Demonstration of the Shorting of the Wavelength and the Resultant Shift of the Standing Wave after the Insertion of the Dielectric Specimen into the Shorted Waveguide System

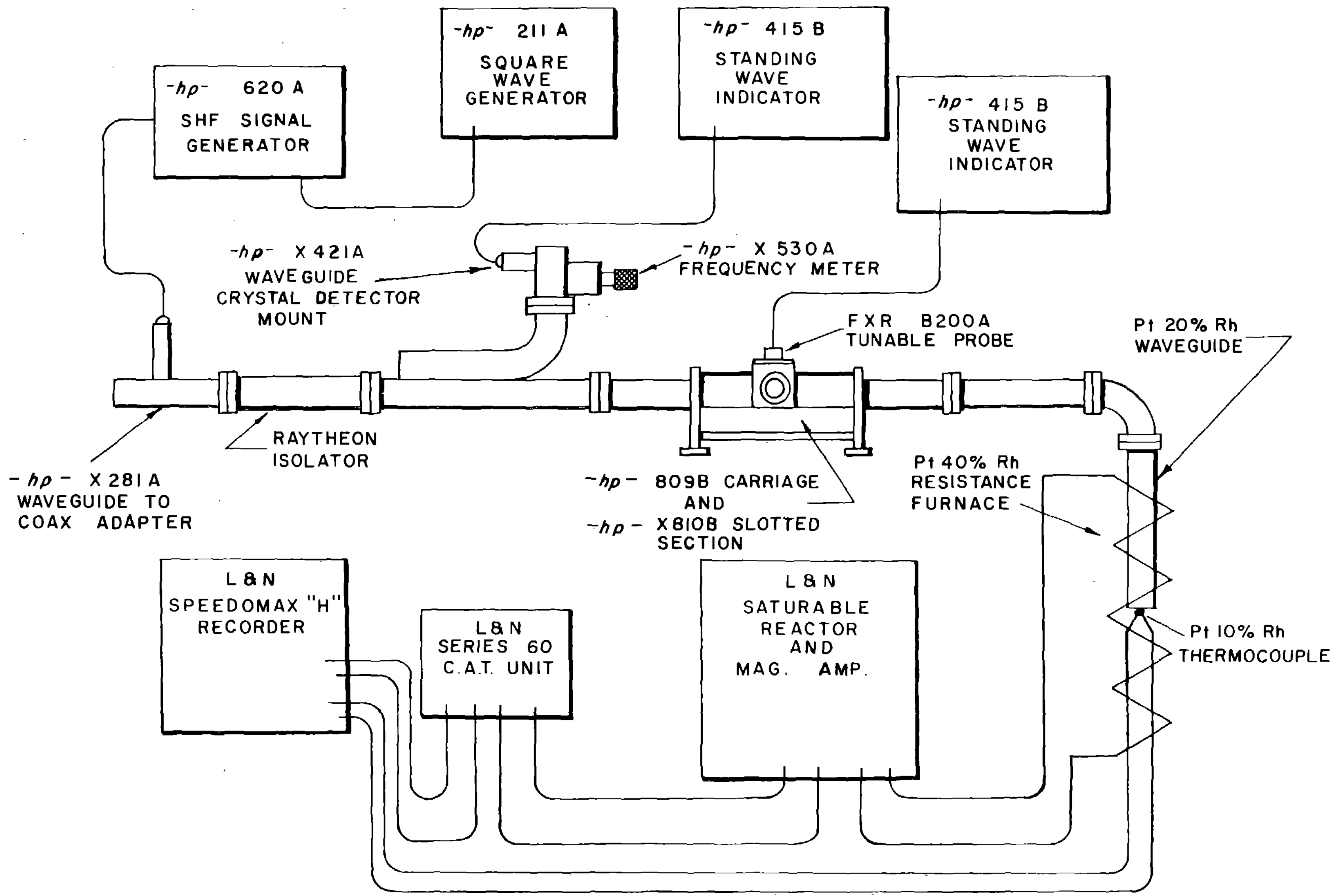

Figure 15 An Arrangement of the Apparatus Used in the Determination of Dielectric Properties by the Use of the Shorted-Circuit-Line Method

The parameter, q, represents the ratio of the guide wavelength in air to that in the sample. The ratio, X_o/λ_g, is computed by means of the following relationship:

$$X_o/\lambda_g = N/2 - d_s/\lambda_g - (X_2 - X_1)\lambda_g,$$

in which N is the minimum positive integer yielding a positive value of X_o/λ_g.

Similarly, a simplified expression of dielectric loss tangent is obtained:

$$\text{loss tan} = \frac{\Delta X}{d_s} \ (Fp) \ (Fq)$$

where ΔX = shift in node width at half-power or 3-db points

$$Fp = 1 - p/k$$

$$Fq = \frac{x + x \tan^2 2\pi \frac{x_o}{\lambda_g}}{x + x \tan^2 x - \tan x}$$

This method yields measurements that are more than sufficient for most engineering applications.

The preceding discussion has been confined to three of the more than thirty available methods for determining dielectric properties of solid dielectrics. Each of the methods described has advantages and disadvantages. However, the researcher or tester who is skilled in any one of the three methods can, with proper precautions, evaluate the dielectric properties of solid dielectrics to within ±1%. Numerous other methods have been eliminated because of one or two of the following disadvantages.

a. Accuracies do not approach the ±1% range which is easily attainable by the three methods discussed.

b. The system is not capable of evaluating both dielectric constant and loss tangent.

c. Inability to attain elevated temperature data.

d. No data available by that method.

Assuming one is familiar with the usual precautions necessary when working with high-frequency equipment, a discussion of the less familiar difficulties will be pursued. Each of the methods described above can produce erroneous data. The extractor should be aware of the errors often made which will affect the reliability of the measurements. Careful attention must be

given to the sample being measured. In the variable-length resonant-cavity method, radial tolerances are not critical; however, the faces must be flat and parallel to within .002 inches. The optimum sample thickness is 60 electrical degrees. This becomes a problem when extending the temperature range. As the temperature increases, the sample expands, thus increasing the electrical thickness. To compensate for this effect, one must use two or more sample thicknesses, depending on the temperature conditions and thermal expansion of the material being tested.

It was mentioned previously that the variable-frequency resonant cavity was made by forming a cavity around the test sample. The three coatings mentioned were silver, platinum paint, and platinum foil. One should be cautioned, however, that the platinum paint has a resistivity 20 times that of copper; therefore one cannot assume the empty cavity conditions. Correction factors must be incorporated into the calculations to overcome this difficulty.

The best way to solve the high-resistivity problem is to avoid using the platinum paint by using .0015" foil. The foil can be applied to most refractories by wrapping the cylindrical sample with the foil, placing it in a tight-fitting carbon sleeve and sintering to about 750°C. If the expansion of the refractory is greater than that of the carbon, the foil will be compressed into a perfect cavity.

Difficulties will arise in forming the cavity around the sample, so one searching for accurate dielectric data must make certain that the researcher or tester encountering these difficulties has become proficient before proceeding with the actual test.

The exact sample fit in the shorted wave guide system is the most critical consideration, since it is necessary that the sample fill the complete end of the waveguide to achieve accurate and reproducible dielectric constant values. Much time and patience is required before one becomes proficient in loading and unloading the waveguide. As the temperature is increased in this system, it is obvious that the sample must expand less than the waveguide. If the sample expands faster than the waveguide, it will distort the waveguide; therefore it is necessary to allow enough clearance at ambient temperature so that the sample has room to expand at elevated temperatures. This condition dictates the necessity for two samples: a tight fitting sample at lower temperatures and a slightly smaller sample for elevated temperatures.

For temperature runs in which the dielectric constant changes appreciably, the method is not always ideal unless two or more sample lengths are used, because the sensitivity and accuracy vary with the electrical length as in the variable-length resonant-cavity method. For maximum sensitivity, the sample should not be a multiple of a half wavelength long. A sample having an electrical wavelength $5\lambda/4$ at room temperature can change to a $3\lambda/2$ sample during the temperature run, and the node shifts due to waveguide expansion become important and limit the accuracy of measurements if one does not take the proper precautions.

8. REFERENCES

Earlier in this report, the total number of documents reviewed during this contract was stated as 7000. It will be noted that the bibliography included with this report contains less than 60 references. This is a direct result of the fact that the majority of those reports reviewed either did not contain information of direct use to the use of nonmetallic inorganic refractory materials for elevated temperature radome use. In addition, the same data concerning dielectric behavior was often referenced many times in many documents. If this was the case, the original reference only was included.

Melpar has had extensive experience in the use of CODEN information retrieval techniques, and this system was planned for use in this final report. (See p. 13 Third Quarterly Report in this series, Oct. 63-Jan. 64). Specific guidance from ASD, however, led Melpar to put CODEN usage in abeyance until possible extension of effort in this program.

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Note: The letter "M" in the reference column of the Location Chart in the Appendix indicates data generated at Melpar, Inc.

APPENDIX

LOCATOR CHART

GRAPHICAL DATA

TABULAR DATA

ELECTRICAL PROPERTIES LOCATOR CHART

DIELECTRIC CONSTANT AND LOSS TANGENT

Trade Designation		% Main Constituent	Gm/Cm^3	Graphical Presentation Figure No.	Tabular Presentation Item No.	Test Method	Tested by	Reference
				Alumina				
Alberox	A-962	-	3.731	54,36	1	VFC*	MIT	15
American	614	96	3.725	36,38	2	VFC	MIT	15
Lava	614	96	3.725	40,41	3	SL**	Melpar	M
	614	96	3.725	37,39	4	SL	Melpar	M
	-	94	3.277	-	8	SL	Melpar	M
	719	94	3.586	45,46	5	VFC	MIT	15
	-	94	-	45,46	6	SL	Melpar	M
	-	94	-	45,46	7	SL	Melpar	M
		98	-	29,30	-	SL	Melpar	M
	576	85	3.277	48,49	9	VFC	MIT	15
Carborundrum	1542	99.5	3.726	-	10	VFC	MIT	15
Coors	AD 995	99.5	3.840	20,22	11	VFC	MIT	15
	AD 995	99.5	3.80	20,22	12	VLC***	Boeing	14
	AD 99	99	3.79	25,27	13	VLC	Boeing	14
	AD 99	99	3.795	27,27	14	VFC	MIT	15
	RR	-	3.80	-	16	VFC	MIT	15
	MC-2014	-	3.772	54,56	15	VFC	MIT	15
Diamonite	P-3142-1	95-97	3.706	52,53	17	VFC	MIT	15
	B-890-2	90-95	3.583	52,53	18	VFC	MIT	15
	P-3662	85-90	3.443	52,53	19	VFC	MIT	15
General Electric Lucalux			3.94	54,56	20	VLC	Boeing	14
	Lucalux		3.963	-	21	VFC	MIT	15

* VFC - Variable Frequency Resonant Cavity
** SL - Shorted Line
***VLC - Variable Length Resonant Cavity

Trade Designation		% Main Constituent	Gm/Cm^3	Graphical Presentation Figure No.	Tabular Presentation Item No.	Test Method	Tested by	Reference
Interpace	TC-352	99	3.78	25,26	22	VLC	Boeing	14
	352	99	-	-	23	SL	Melpar	37
	351	97.6	-	33,34	24	SL	Melpar	37
Melpar		99.5	-	19,22	-	SL	Melpar	M
		99	3.81	-	45	SL	Melpar	M
		99	3.779	-	46	SL	Melpar	M
		96	3.65	37,39	47	SL	Melpar	M
		94	3.59	45,46	48	SL	Melpar	M
Minn. Honeywell								
	A-203	95	3.598	40,41	25	VFC	MIT	15
	A-127	85	3.326	46,47	26	VFC	MIT	15
Natl. Beryllia								
	Alox	-	3.736	55,56	27	VFC	MIT	15
Norton		99.5	3.828	19,22	28,29	VFC	MIT	15
Silk City	SC-98D	98	-	31,32	30	SL	Melpar	M
	SC-85D	85	-	50,51	31	SL	Melpar	M
U.S.Stoneware	610	99	3.836	26,28	32	VFC	MIT	15
	A-312	96	3.508	36,38	33	VFC	MIT	15
	A-212	96	3.583	36,38	34	VFC	MIT	15
	A-216	85	3.457	48,49	35	VFC	MIT	15
	AL-Std.	-	3.706	54,56	36	VFC	MIT	15
Wesgo	AL-1009	99.85	3.816	16,17	37	VFC	MIT	14
	AL-995	99.5	3.758	19,22	38	VFC	MIT	15
	AL-995	99.5	3.71-3.77	-	39	VLC	Boeing	14
	AL-995	99.5	-	19,22	40	SL	Melpar	37
	AL-300	97.6	3.765	33,34	41	VFC	MIT	15
	300	97.6	-	33,34	42	SL	Melpar	37

Beryllia

Trade Designation	% Main Constituent	Gm/Cm^3	Graphical Presentation Figure No.	Tabular Presentation Item No.	Test Method	Tested by	Reference
Amer. Lava 754	99.5	-	64,50	49,50	SL	Melpar	M
735	98	-	64,65	51,52	SL	Melpar	M
Atomics Intl. -	99	3.00	62,63	53	SL	Melpar	37
Beryllium Corp. Berylco	99.7		62,63	54	VLC	Boeing	14
Brush Beryllium F-1-7	99.5	2.90	68,69	55	SL	Melpar	M
B-6-11	99	2.82	68,69	56	SL	Melpar	M
B-7	-	-	68,69	57	SL	Melpar	M
F-1-10	-	-	68,69	58	SL	Melpar	M
F-1-7	99.5	2.904	66,67	59	VFC	MIT	15
B-6	98.5	2.862	66,67	60	VFC	MIT	15
B-7-6	-	2.791	66,67	61	VFC	MIT	15
B-7-37	-	2.883	66,67	62	VFC	MIT	15
Coors Porcelain BD-98	98	2.82	58,59	63	VLC	Boeing	14
BD-932	-	2.87	58,59	64	VLC	Boeing	14
Natl Beryllia Berlox	99	2.74-2.80	60,61	65	VLC	Boeing	14
-	-	2.822	60,61	66	VFC	MIT	15
Miscellaneous -	99.5	-	62,63	67	SL	Melpar	M

Boron Nitride

Trade Designation	% Main Constituent	Gm/Cm^3	Graphical Presentation Figure No.	Tabular Presentation Item No.	Test Method	Tested by	Reference
Carborundum	-	2.10	91,92	69	VLC	Boeing	14
	-	2.065	91,92	70	VFC	MIT	15
	-	2.135	91,92	71	VFC	MIT	15
	-	-	91,92	68	SL	Melpar	M

Pyroceram

Trade Designation		% Main Constituent	Gm/Cm^3	Graphical Presentation Figure No.	Tabular Presentation Item No.	Test Method	Tested by	Reference
Corning	9606	-	2.607	83, 84	72	VFC	MIT	15
	9606	-	2.59	83, 84	73	VLC	Boeing	14
	9606	-	-	83, 84	75	SL	Melpar	M
	9606	-	-	-	74	-	-	38
	9608	-	-	85, 86	76	-	-	4
Spinel								
Boeing		-	3.50	89, 90	101	VLC	Boeing	14
Magnesia								
Boeing		-	3.42	87, 88	100	VLC	Boeing	14
Minn.-Honeywell		-	3.515	87, 88	99	VFC	MIT	15
Silicates								
American Optical								
Amersil (Commercial)				73, 74	77	SL	Melpar	M
Amersil (Translucent)			2.125	73, 74	78	VFC	MIT	15
Amersil (Clear)			2.196	73, 74	79	VFC	MIT	15
Corning	7900	96	2.18	71, 72	80	-	Corning	8
	7941	-	1.962	76, 77	81	VFC	MIT	15
	7940M	-	1.96	76, 77	82	VLC	Boeing	14
	915C	-	2.19	71, 72	83	VLC	Boeing	14

Trade Designation		% Main Constituent	Gm/Cm^3	Graphical Presentation Figure No.	Tabular Presentation Item No.	Test Method	Tested by	Reference
Georgia Tech.	A-694-12	-	-	81, 82	85	SL	Melpar	38
	A-694-13	-	-	81, 82	86	SL	Melpar	38
	A-694-1	-	-	77, 78	87	SL	Melpar	38
	A-694-2	-	-	77, 80	88	SL	Melpar	38
	A-694-3	-	-	77, 78	89	SL	Melpar	38
	A-694-6	-	-	77, 78	90	SL	Melpar	38
	A-694-7	-	-	79, 80	91	SL	Melpar	38
	A-694-8	-	-	79, 80	92	SL	Melpar	38
	A-694-9	-	-	79, 80	93	SL	Melpar	38
	A-694-10	-	-	79, 80	94	SL	Melpar	38
	A-694-11	-	-	81, 82	95	SL	Melpar	M
Miscellaneous		-	-	-	98	-	-	38

ELECTRICAL PROPERTIES LOCATOR CHART

VOLUME RESISTIVITY

Trade Designation		% Main Constituent	Gm/Cm^3	Graphical Presentation Figure No.	Tabular Presentation Item No.	Test Method	Tested by	Reference
				Alumina				
American Lava	748	98.0		94	108	-	-	2
	614	96.0		94	109	-	-	2
	719	94.0		94	110	-	-	2
	576	85.0		94	111	-	-	2
Coors	AD99	99.0		93	112	-	-	25
	AD96	96.0		93	113	-	-	25
	AD94	94.0		93	114	-	-	25
	AD85	85.0		93	115	-	-	25
Diamonite	P-3142-1	95-97		-	116	-	-	27
	B-890-2	90-95		-	117	-	-	27
	P-3662	85-90		-	118	-	-	27
Silk City	SC98D	98		96	119	-	-	27
Wesgo	AL1009	99.85		95	120	-	-	26
	AL995	99.5		-	121	-	-	26
	AL300	97.6		95	122	-	-	26
	AL400	95.0		95	123	-	-	20
Miscellaneous		99.9		96	124			
				Beryllia				
American Lava	754	99.5		98	125	-	-	2
Coors	BD995	99.5		98	126	Potential Drop	Melpar	M
	BD99	99.0		97	127	Potential Drop	Melpar	M
	BD98	98.0		97	128	Potential Drop	Melpar	M
	BD96	96.0		97	129	Potential Drop	Melpar	M
Miscellaneous		-		99	130	Potential Drop	Foex	33

Trade Designation	% Main Constituent	Gm/Cm^3	Graphical Presentation Figure No.	Tabular Presentation Item No.	Test Method	Tested by	Reference
			Silicates				
Forsterite	-		103	138	DC Bridge	Ibid	33
L-5 Steatite	-		103	139	DC Bridge	Ibid	33
L-4 Steatite	-		103	140	DC Bridge	Comeforo Hatch	33
Steatite	-		103	141	DC Bridge	Hauth	33
Corning 7900	-		-	131		Corning	8
Corning 7900M	-		101	132,133	-	Corning	8
			Pyroceram				
Corning 9606	-		101	134	-	Corning	8
Corning 9608	-		-	135	-	Corning	8
			Spinel				
-	-		102	133	-		33
			Boron Nitride				
-	-		100	136	-	Taylor	34
			Magnesia				
-	-		102	137	Potential Drop	Weigelt & Haase	33

ELECTRICAL PROPERTIES LOCATOR CHART

DIELECTRIC STRENGTH

Trade Designation	% Main Constituent	Graphical Presentation Figure No.	Tabular Presentation Item No.	Test Method	Tested by	Reference
			Alumina			
Coors AD 99	99.0		142	-	-	25
Coors AD 96	96.0		143	-	-	25
Diamonite P-3142-1	95-97		144	-	-	27
Diamonite B-890-2	90-95		145	-	-	27
Diamonite P-3662	85-90		146	-	-	27
Wesgo AL 995	99.5		147	-	-	26
Wesgo AL 300	97.6		148	-	-	26
Wesgo AL 400	95.0		149	-	-	26
			Beryllia			
Brush Beryllium B7	-		150	AC HiPot	Melpar	M
Coors BD 98	98.0		151	-	-	25
BD 96	96.0		152	-	-	25
National Beryllia Berlox	99.0		153	-	-	20

THERMAL PROPERTIES LOCATOR CHART

ALUMINA

Trade Designation		% Main Constituent	Graphical Presentation Figure No.	Tabular Presentation Item No.	Test Method	Tested by	Reference
Specific Heat							
Coors	AD 995	99.5	-	155	Bunsen Ice Calorimeter	Melpar	39
	AD 99	99	-	158	-	-	7
Interpace		99.5	-	156	Bunsen Ice Calorimeter	Melpar	39
Norton		99.5	-	157	Bunsen Ice Calorimeter	Melpar	39
Unknown	-	99.97-99.98	105	154	Bunsen Ice Calorimeter	NBS	60
Thermal Conductivity							
Coors	AD 995	99.5	-	168	Radial Heat Flow	Melpar	39
	AD 995	99.5	-	170	-	-	25
	AD 995	99.5	-	170	-	-	25
	AD 995	99.5	-	169	-	-	7
	AD 99	99	-	171			7
	AD 94	94	-	172			25
	AD 85	85	-	173			25
Silk City	SC 99P	99	111	174	Radial Heat Flow	Melpar	M

Trade Designation		% Main Constituent	Graphical Presentation Figure No.	Tabular Presentation Item No.	Test Method	Tested by	Reference
	SC 98D	98	111	175	Radial Heat Flow	Melpar	M
	SC 85D	85	111	176	Radial Heat Flow	Melpar	M
				Thermal Expansion			
Coors	AD 995	99.5	131	199	Sapphire Dilatometer	Melpar	39
	AD 995	99.5	132	200	Sapphire Dilatometer	Melpar	39
	AD 995	99.5	-	201			25
	AD 995	99.5	-	202			7
	AD 99	99	-	203			25
	AD 99	99	-	204			7
	AD 96	96	-	205			25
	AD 94	94	-	206			25
	AD 85	85	-	207			25
Interpace		99.5	131	208	Sapphire Dilatometer	Melpar	39
		99.5	132	209	Sapphire Dilatometer	Melpar	39
Norton		99.5	131	210	Sapphire Dilatometer	Melpar	39
		99.5	132	211	Sapphire Dilatometer	Melpar	39
Wesgo	AL-1009	99.85		213			26
	AL-995	99.5	-	214			26
	AL-300	97.6	-	215			26
	AL-400	95	-	216			26
				Emissivity			
Coors	AD 995	99.5	123	225	Total Normal	Melpar	39
	AD 995	99.5	118	226	Total Normal	Melpar	39
	AD 995	99.5	122	227	Total Normal		7

Trade Designation	% Main Constituent	Graphical Presentation Figure No.	Tabular Presentation Item No.	Test Method	Tested by	Reference
Interpace	99.5	121	228	Total Normal	Melpar	39
	99.5	121	229	Total Normal	Melpar	39
Norton	99.5	120	230	Total Normal	Melpar	39
	99.5	120	231	Total Normal	Melpar	39
LA-603	-	119	232	Total Normal		32
RA-4213	-	119	233	&		32
ROKIDE	-	-	234	Normal Spectral		32

ALUMINA WITH ADDATIVES

Thermal Conductivity

Trade Designation	% Main Constituent	Graphical Presentation Figure No.	Tabular Presentation Item No.	Test Method	Tested by	Reference
6.42% Cr_2O_3		113	180		Lee & Kingery	35
2.88% Cr_2O_3		113	181		Lee & Kingery	35
1.26% Cr_2O_3		113	182		Lee & Kingery	35
1.10% Cr_2O_3		114	183		Lee & Kingery	35
.75 Cr_2O_3		114	184		Lee & Kingery	35
.247 Cr_2O_3		113	185		Lee & Kingery	35
.16 Cr_2O_3		114	186		Lee & Kingery	35
12.5% Porosity		112	177		Lee & Kingery	35
3.0% Porosity		112	178		Lee & Kingery	35
.25% Porosity		112	179		Lee & Kingery	35

FUSED SILICA

Specific Heat

Trade Designation	% Main Constituent	Graphical Presentation Figure No.	Tabular Presentation Item No.	Test Method	Tested by	Reference
Corning 7940	-	109	163	-	-	8
7941	-	109	164	-	-	11
7900	96.3	110	165			17

Trade Designation	% Main Constituent	Graphical Presentation Figure No.	Tabular Presentation Item No.	Test Method	Tested by	Reference
			Thermal Conductivity			
Corning 7940	-	117	188			8
7941	-	117	189			11
(Vycor) 7900	96.3	116	187			17
UNK Slip Cast	-	117	190			40
UNK Foamed Clear		117	191			40
			Thermal Expansion			
Corning 7940	-	-	-	-	-	8
(Vycor) 7900	96.3	-	224	-	-	17
			Thermal Diffusivity			
Corning 7940	-	137	245			8
7941		137	246			11
UNK Slip Cast	-	-	247			40
UNK Foamed Clear	-	-	248			40
			Emissivity			
Corning 7940	-	-	241			8
(Vycor) 7900	96.3	-	240			32
UNK Slip Cast	-	-	242			40
UNK Foamed Clear	-	-	-			40
			BERYLLIA			
			Specific Heat			
Coors	100	107	159	Coors Rocketdyne Alfred	Coors Rocketdyne Alfred	7
BD-98	98	-	160	-	-	25
BD-96	96	-	161		-	25

Trade Designation	% Main Constituent	Graphical Presentation Figure No.	Tabular Presentation Item No.	Test Method	Tested by	Reference
UNK	-			-		36
			Thermal Conductivity			
Brush Beryllium	98.5	115	195	Radial Heat Flow	Melpar	M
UNK	2.7-2.86 dense	115	196	Comparative Heat Flow	Kingery	59
UNK	3.01 dense	115	197	Comparative Heat Flow	Kingery	59
UNK	2.62 dense	115	198	Steady State Longitudinal Heat Flow	NBS Washington	59
			Thermal Expansion			
Brush Beryllium	98.5	-	-	Sapphire Dilatometer	Melpar	M
Coors	100	134	217	-	-	7
BD-98	98	-	218	-	-	25
BD-96	96	-	219	-	-	25
UNK	-	135	220	-	-	59
UNK	-	135	221	-	-	59
UNK	-	135	222	-	-	59
			Emissivity			
UNK	-	-	235	Total	-	59
Brush Beryllium SP	-	125	236	Total	-	59
Brush Beryllium SP	-	125	238	Total	-	59
UNK	-	-	237	Spectral	-	59
Brush Beryllium SP	-	125	239	Spectral	-	59

PYROCERAM

Trade Designation		% Main Constituent	Graphical Presentation Figure No.	Tabular Presentation Item No.	Test Method	Tested by	Reference
				Specific Heat			
Corning	9606		108	166	ASTM C351-597	Corning	8
	9608		108	167			8
				Thermal Conductivity			
Corning	9606		116	193	Calculated	Corning	8
				Thermal Exapnsion			
Corning	9606		-	223		Corning	8
				Thermal Diffusivity			
Corning	9606		116	249	CGW		8
	9608		116	250			8
				Emissivity			
Corning	9606		127	243	Total Normal &		31
	9608		127	244	Normal Spectral		31

MECHANICAL PROPERTIES LOCATOR CHART

ALUMINA

Trade Designation		% Main Constituent	Graphical Presentation Figure No.	Tabular Presentation Item No.	Test Method	Tested by	Reference
Compressive Strength							
Coors	AD 995	99.5	-	251			25
	AD 99	99	-	252			25
	AD 96	96	-	253			25
	AD 94	94	-	254			25
	AD 85	85	-	255			25
Wesgo	AL 1009	99.85	-	256			26
	AL 995	99.5	-	257			26
	AL 300	97.6	-	258			26
	AL 400	95	-	259			26
Tensile Strength							
Coors	AD 995	99.5	138	260		Melpar	39
	AD 99	99	-	261			25
	AD 99	99	-	262			7
	AD 96	96	-	263			25
	AD 94	94	-	264			25
	AD 85	85	-	265			25
Interpace		99.5	139	266		Melpar	39
Norton		99.5	139	267		Melpar	39
Young's Modulus - Shear Modulus - Poisson's Ratio							
Coors	AD 995	99.5	149	284	Sonic	Melpar	39
	AD 995	99.5	149	285	Sonic	Melpar	39
	AD 995	99.5	149	286		Melpar	25
	AD 995	99.5	150	287			7
	AD 99	99	150	288			25
	AD 99	99	-	289			7

Trade Designation		% Main Constituent	Graphical Presentation Figure No.	Tabular Presentation Item No.	Test Method	Tested by	Reference
	AD 96	96	-	291			25
	AD 94	94	-	292			25
	AD 85	85	-	293			25
Interpace		99.5	149	294	Sonic	Melpar	39
		99.5	149	295	Sonic	Melpar	39
Norton		99.5	149	296	Sonic	Melpar	39
		99.5	149	297	Sonic	Melpar	39
				Flexural Strength			
Coors	AD 995	99.5	144	268	1/4 Point	Melpar	39
	AD 995	99.5	144	269	1/4 Point	Melpar	39
	AD 995	99.5	144	270	-	-	25
	AD 99	99.0	-	271			7
	AD 99	99.0	145	272			25
	AD 96	96.0	-	273			25
	AD 94	94.0	-	274			25
	AD 85	85.0	-	275			25
Interpace		99.5	144	276	1/4 Point	Melpar	39
		99.5	144	277	1/4 Point	Melpar	39
Norton		99.5	144	278	1/4 Point	Melpar	39
		99.5	144	279	1/4 Point	Melpar	39
Wesgo	AL 1009	99.85	-	280			26
	AL 995	99.5	-	281			26
	AL 300	97.6	-	282			26
	AL 400	95.0	-	283			26
				FUSED SILICA			
				Flexural Strength			
Corning	7941		148	307	Single Point Loading	Corning	11

Trade Designation		% Main Constituent	Graphical Presentation Figure No.	Tabular Presentation Item No.	Test Method	Tested by	Reference
			Young's Modulus – Shear Modulus – Poisson's Ratio				
Corning	7941		153,159	307	Sonic		11
				BERYLLIA			
				Compressive Strength			
Coors							29
	BD 98	98	-	300			25
	DD 96	96	-	299			25
Miscellaneous							30
				Tensile Strength			
Coors		100	140	298			7 30
				Flexural Strength			
Coors	BD 98	98	146	300			25
	BD 96	96	146	299			25
				Young's Modulus			
Coors	BD 98	98	-	300			25
	BD 96	96	-	299			25
				PYROCERAM			
				Tensile Strength			
Pyroceram	9606		142	303		Melpar	18
	9606		142	304		Melpar	18

Trade Designation	% Main Constituent	Graphical Presentation Figure No.	Tabular Presentation Item No.	Test Method	Tested by	Reference
			Flexural Strength			
Pyroceram 9606		147	304		Melpar	18
9606			303		Melpar	18
9606			302		Corning	11
			Young's Modulus - Shear Modulus - Poisson's Ratio			
Pyroceram 9606		152	304	Sonic Resonance	Melpar	18
9606		-	-	Sonic Resonance	Melpar	18
9606		152	302	Sonic Resonance	Corning	8 % 11

MAGNESIA (MgO)

Trade Designation	% Main Constituent	Graphical Presentation Figure No.	Tabular Presentation Item No.	Test Method	Tested by	Reference
			Tensile Strength - Young's Modulus - Shear Modulus			
Unknown		141,151,157	305			29

SPINEL ($MgOAl_2O_3$)

Trade Designation	% Main Constituent	Graphical Presentation Figure No.	Tabular Presentation Item No.	Test Method	Tested by	Reference
			Tensile Strength - Compressive Strength - Young's Modulus - Shear Modulus			
Unknown		154,160	306			61

SECTION A
GRAPHICAL DATA

LEGEND EXPLANATION FOR GRAPHICAL PRESENTATIONS

Each graph of dielectric constant and loss tangent has a legend describing the individual material curves by (1) manufacturer, (2) per cent main constituent, (3) testing agency, and (4) test frequency, in that order. The numbers on the individual curves correspond to the numbers on the legend.

The information on the thermal and mechanical properties graphs is limited to manufacturer and material.

RD 1046

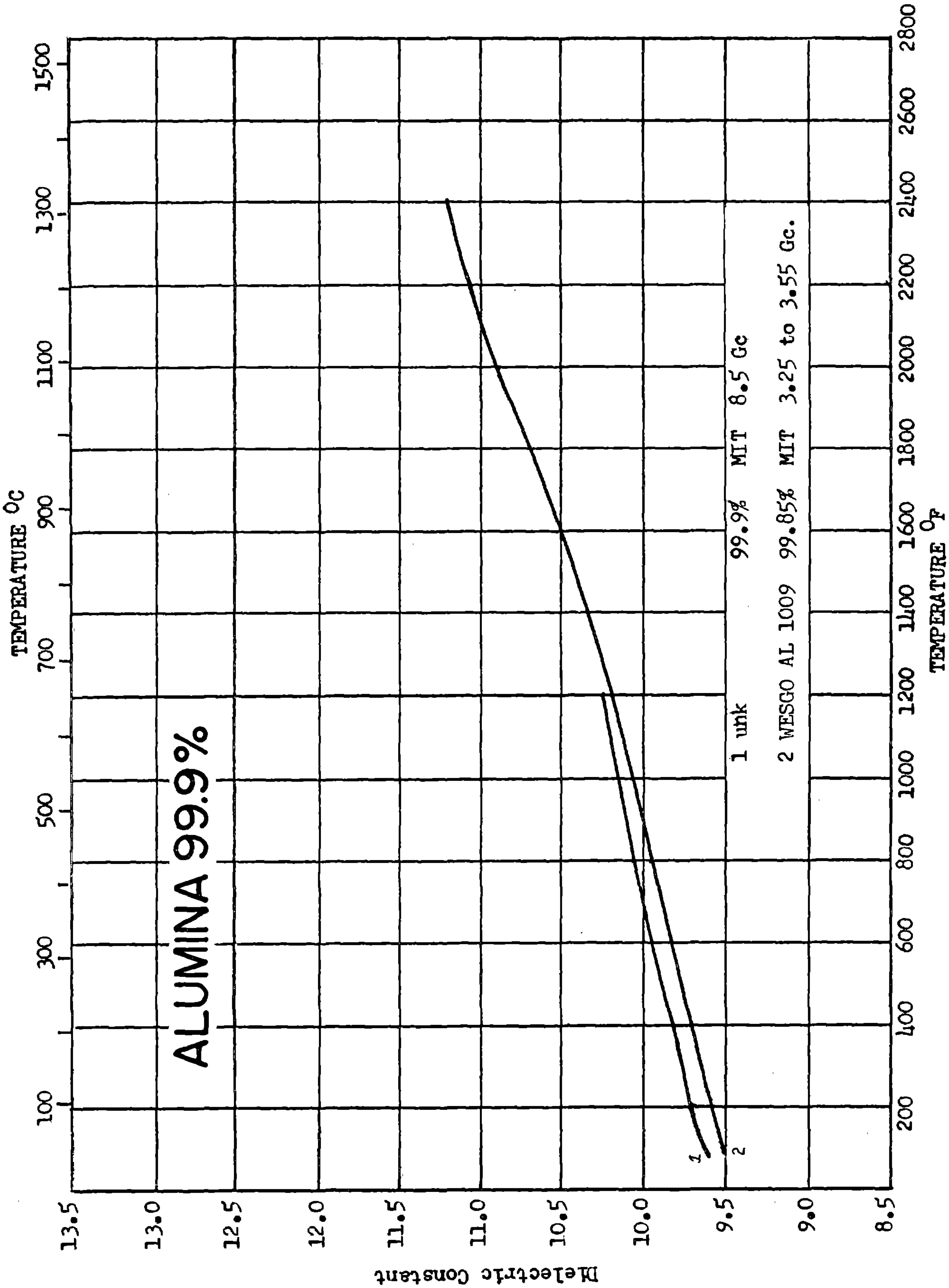


Figure 16

RD 1045

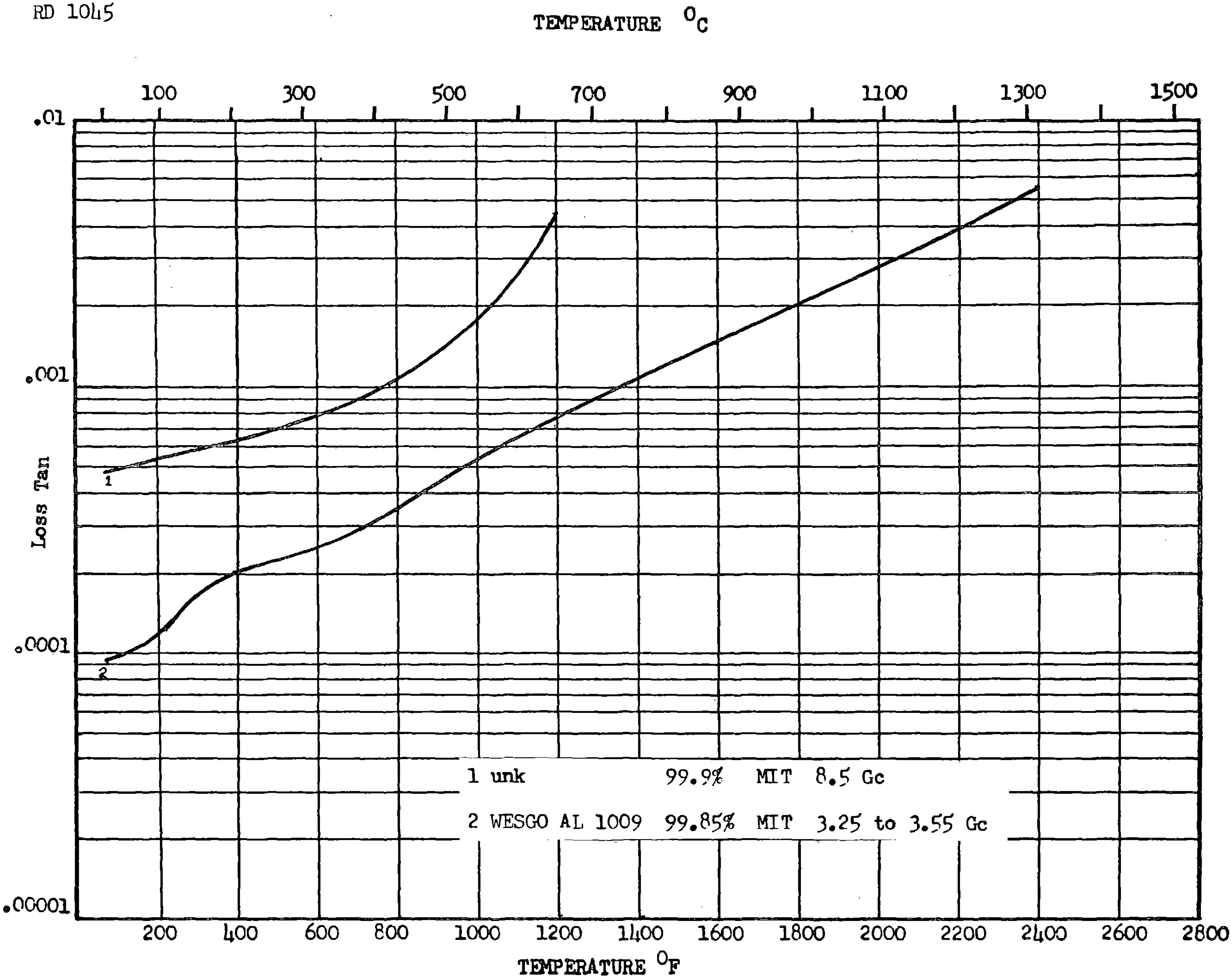


Figure 17

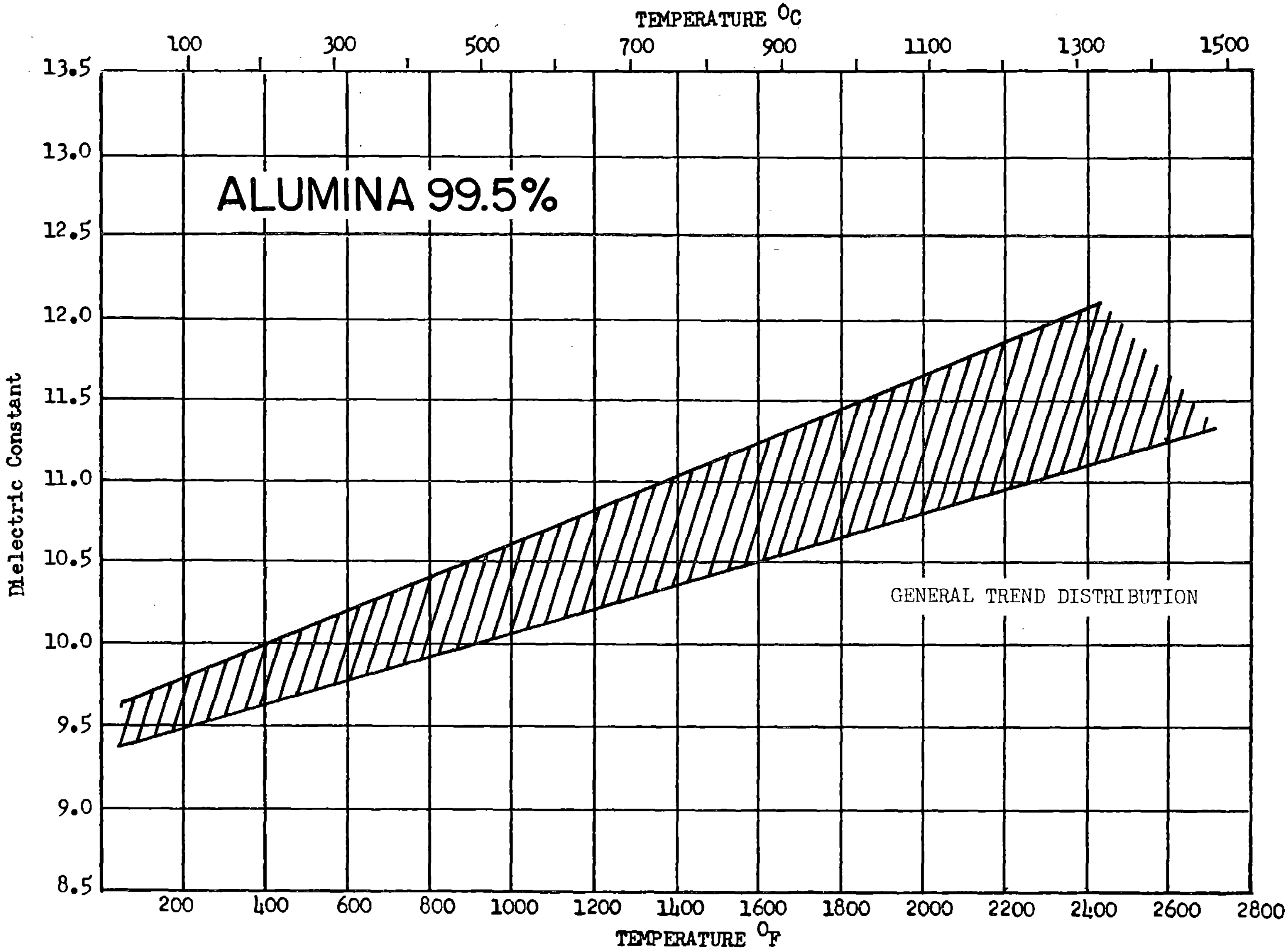

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
13.5
13.0
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
Dielectric Constant
ALUMINA 99.5%
GENERAL TREND DISTRIBUTION
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 18

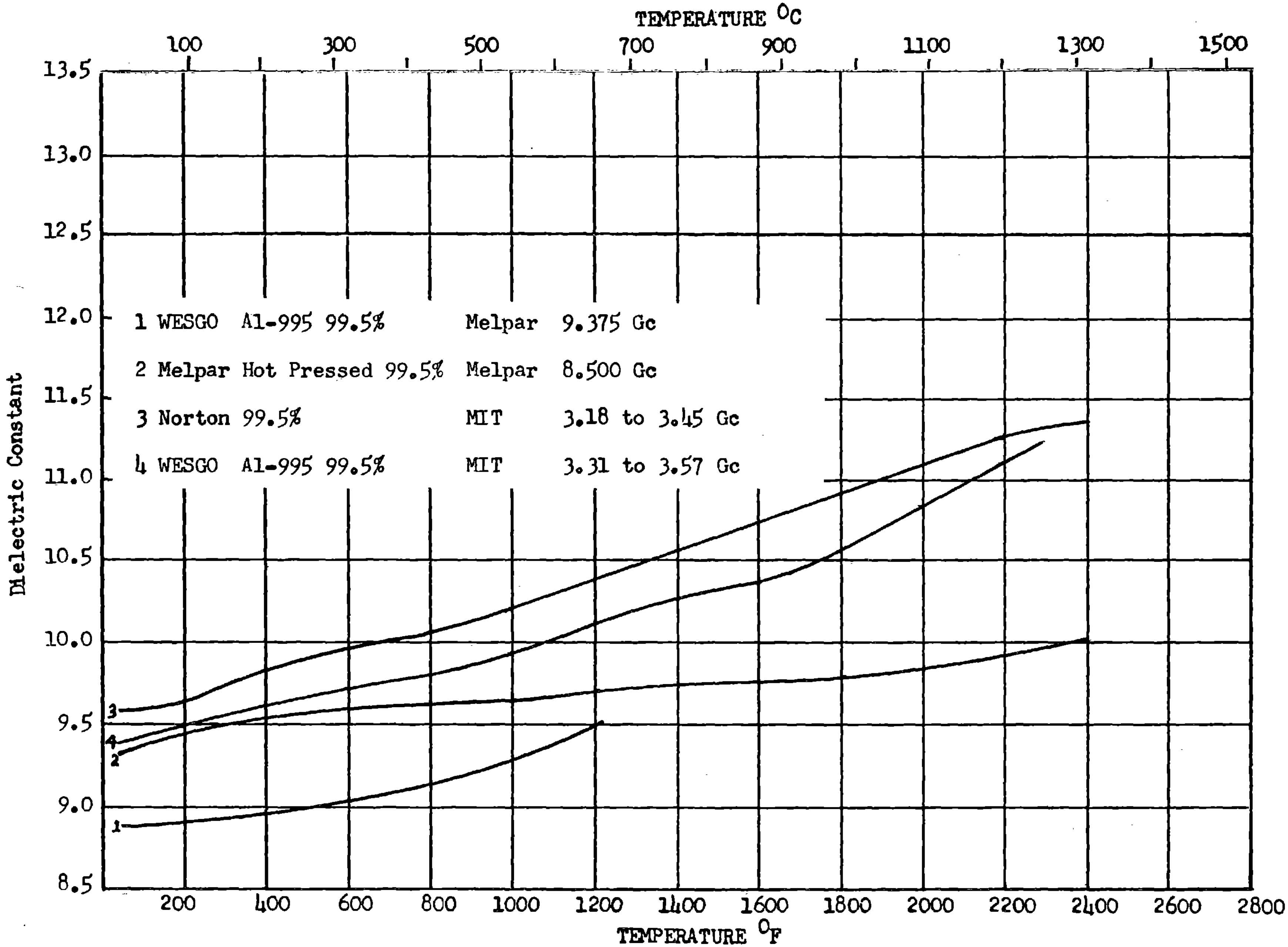

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
13.5
13.0
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
Dielectric Constant
1 WESGO Al-995 99.5% Melpar 9.375 Gc
2 Melpar Hot Pressed 99.5% Melpar 8.500 Gc
3 Norton 99.5% MIT 3.18 to 3.45 Gc
4 WESGO Al-995 99.5% MIT 3.31 to 3.57 Gc
1
2
3
4
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 19

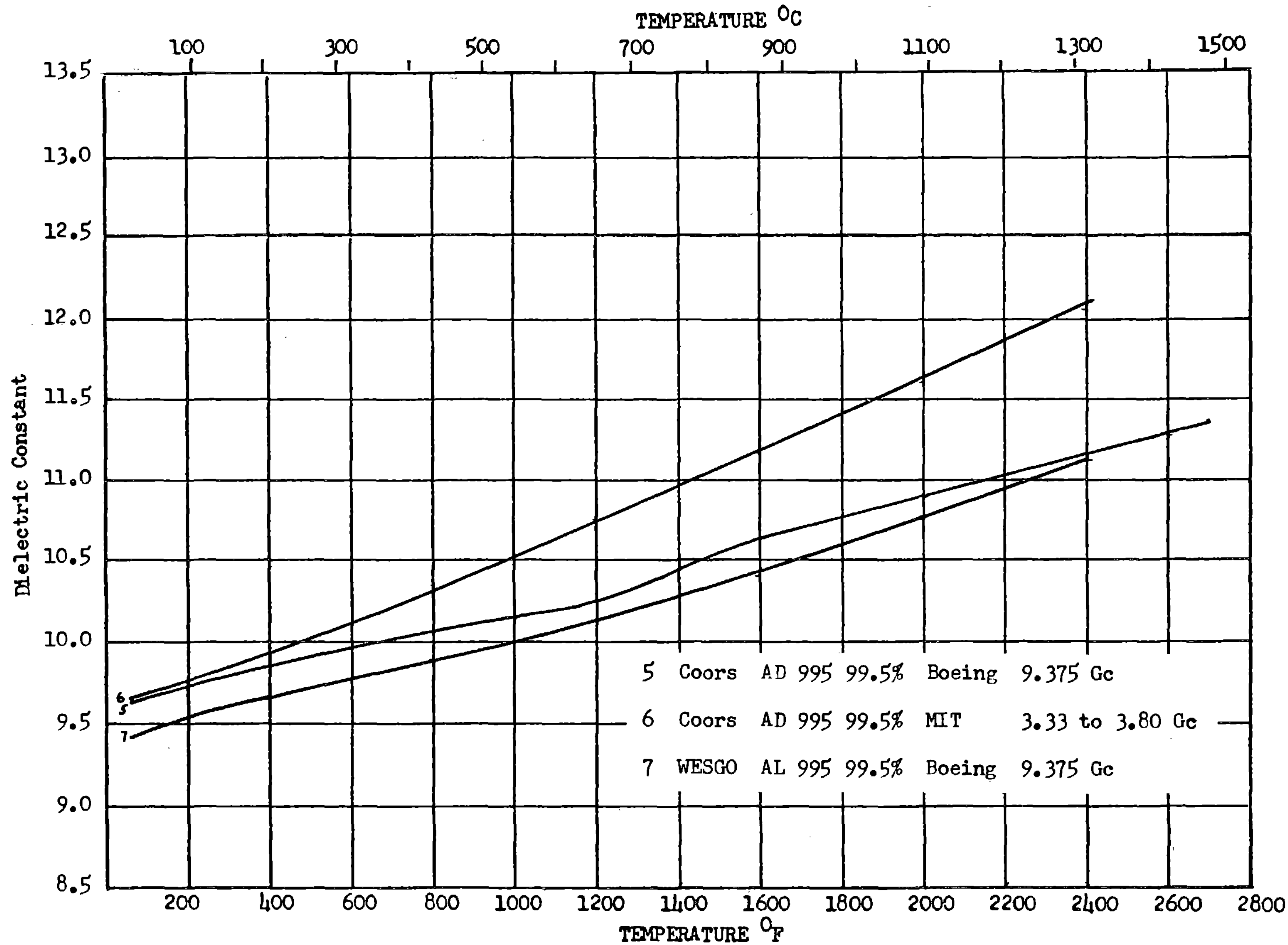

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
Dielectric Constant
13.5
13.0
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
5 Coors AD 995 99.5% Boeing 9.375 Gc
6 Coors AD 995 99.5% MIT 3.33 to 3.80 Gc
7 WESGO AL 995 99.5% Boeing 9.375 Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 20

RD 1045

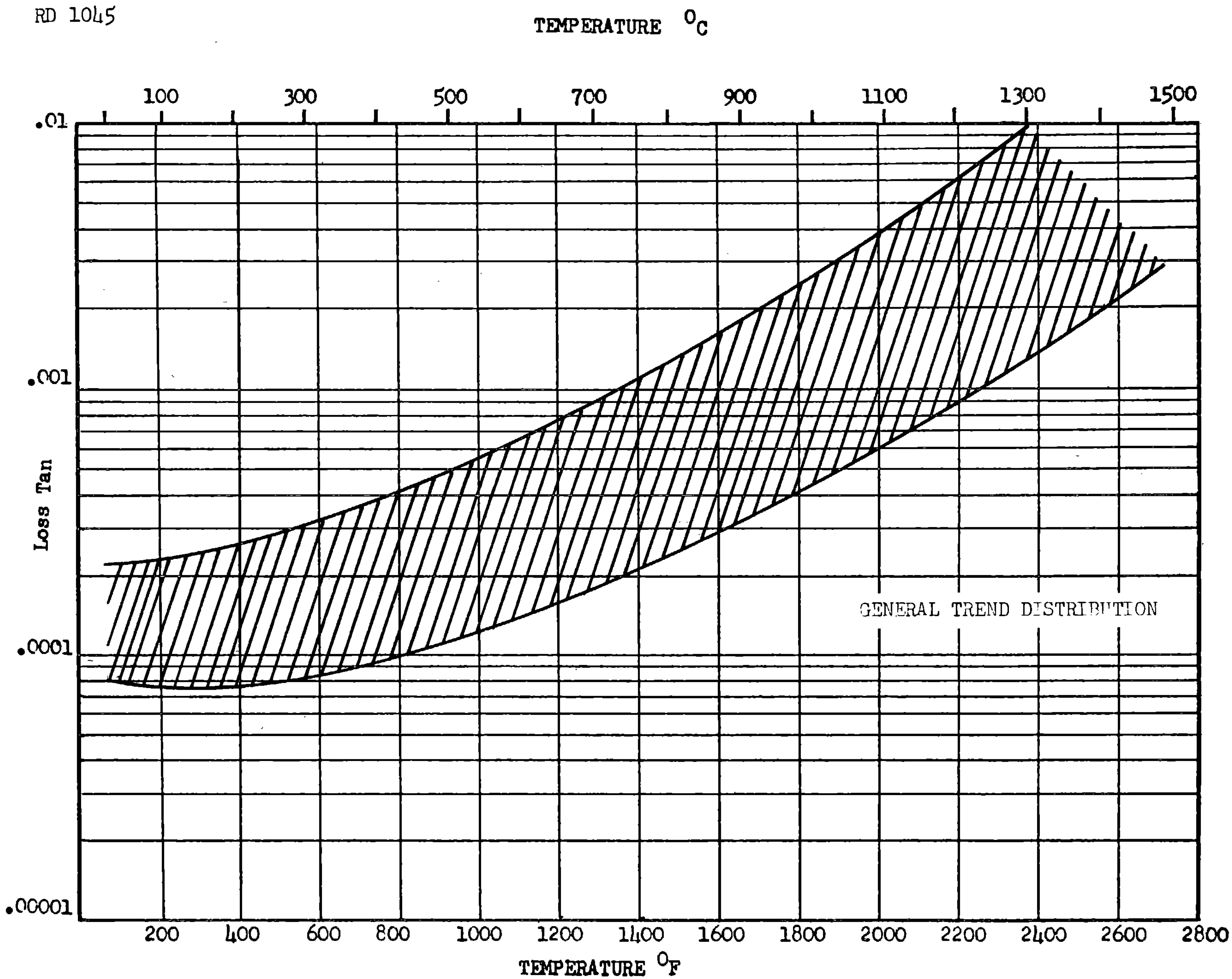


Figure 21

RD 1045

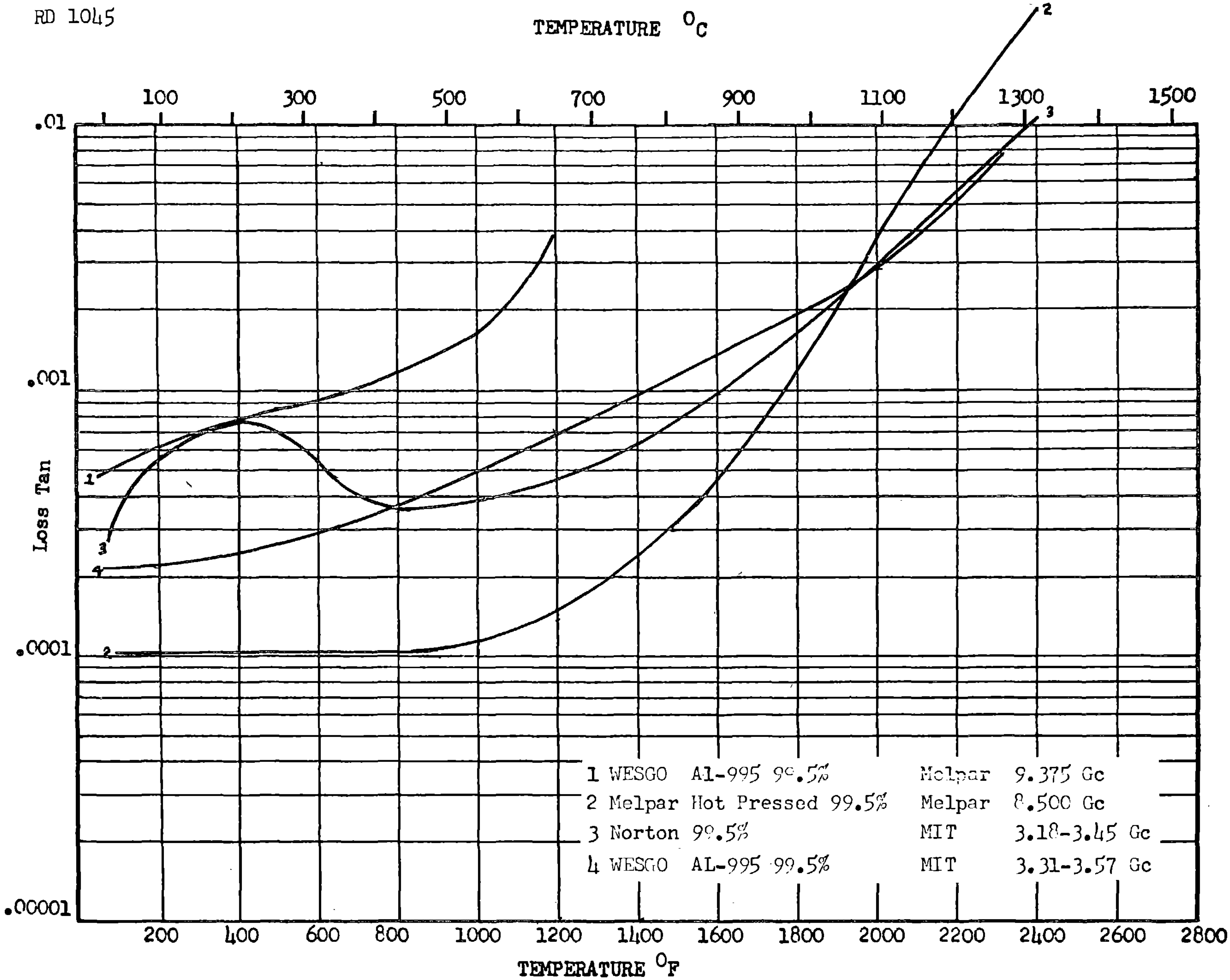


Figure 22

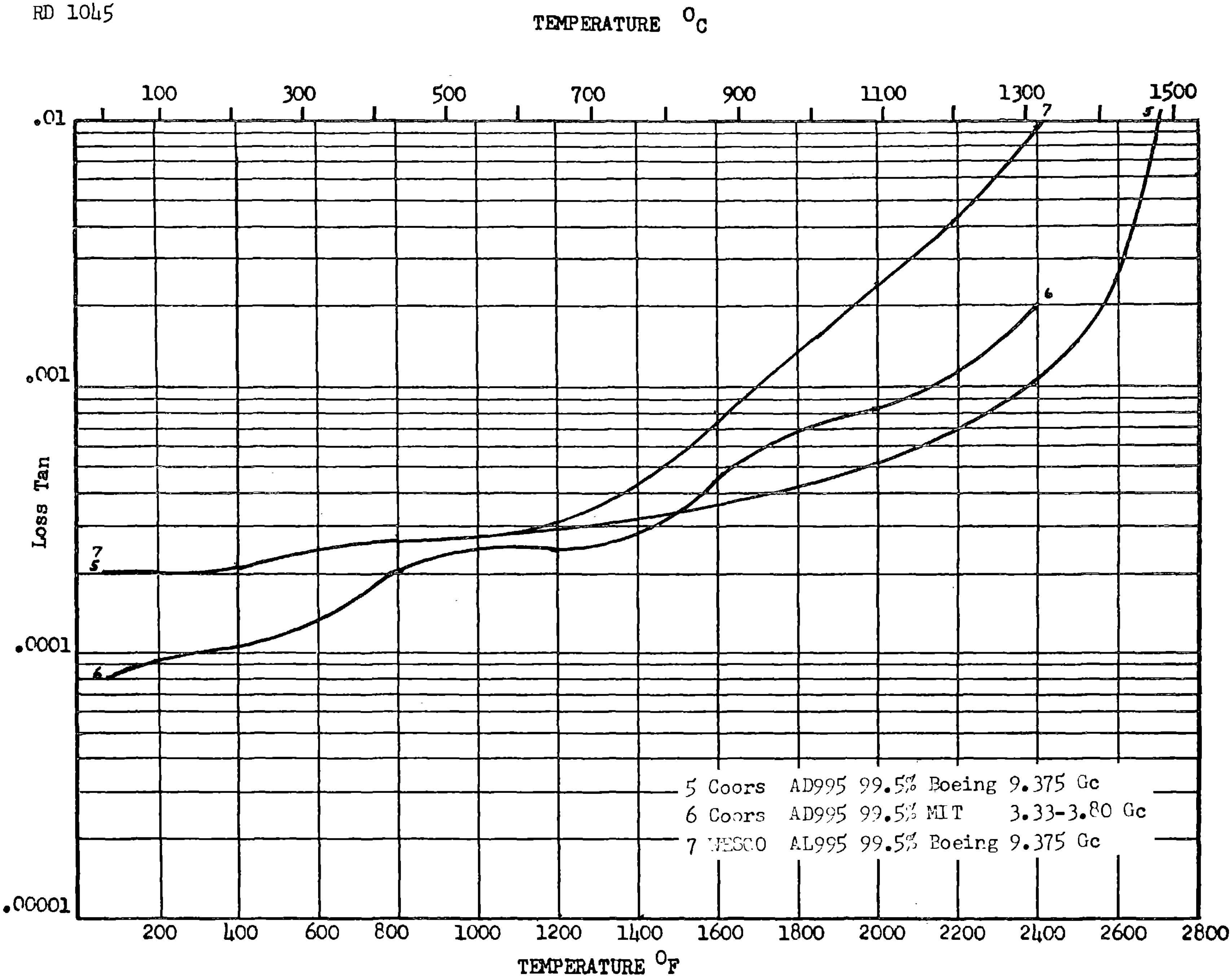

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.01
.001
.0001
.00001
Loss Tan
7
5
6
5 Coors AD995 99.5% Boeing 9.375 Gc
6 Coors AD995 99.5% MIT 3.33-3.80 Gc
7 WESCO AL995 99.5% Boeing 9.375 Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 23

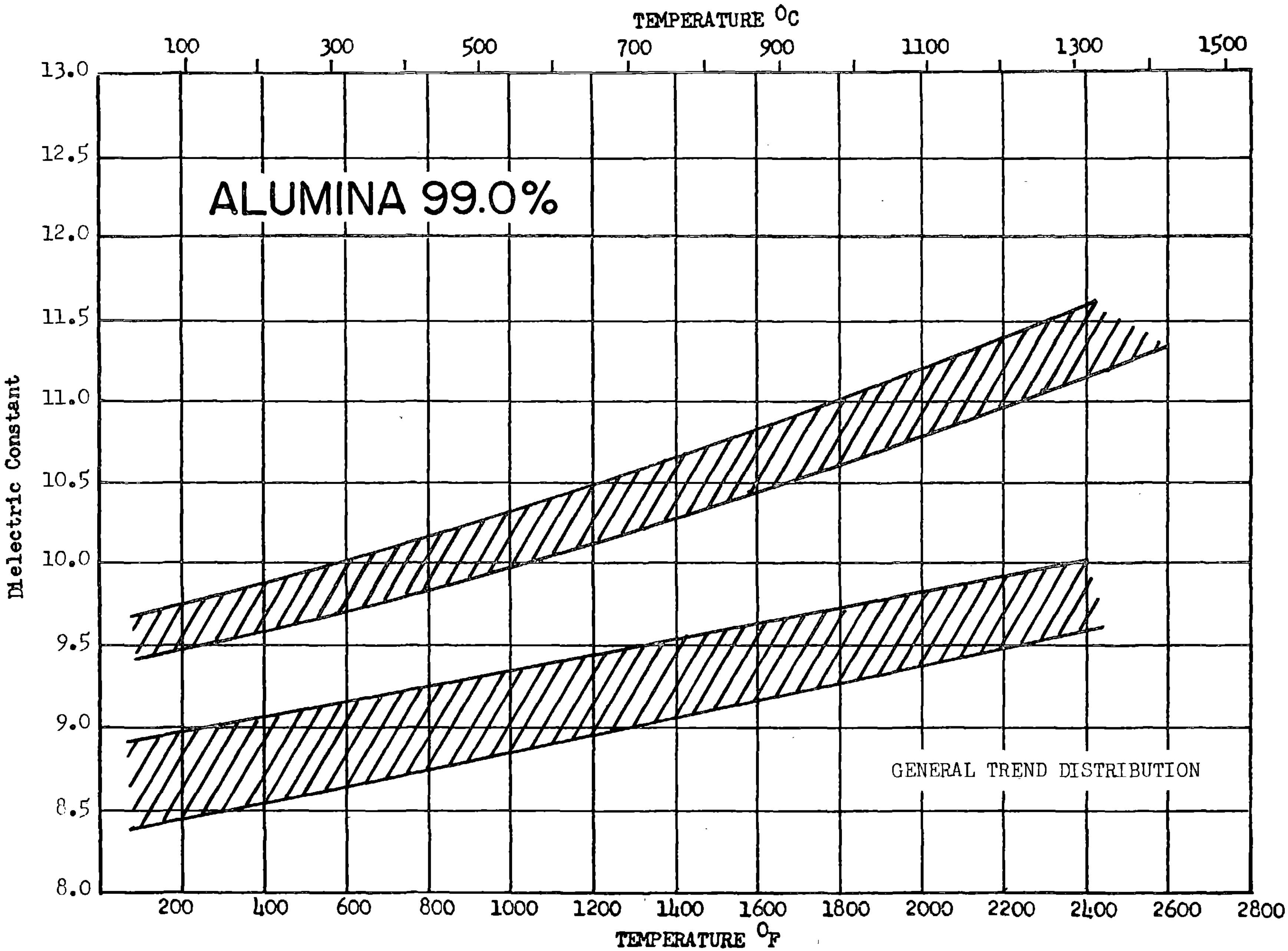

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
ALUMINA 99.0%
Dielectric Constant
13.0
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
GENERAL TREND DISTRIBUTION
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 24

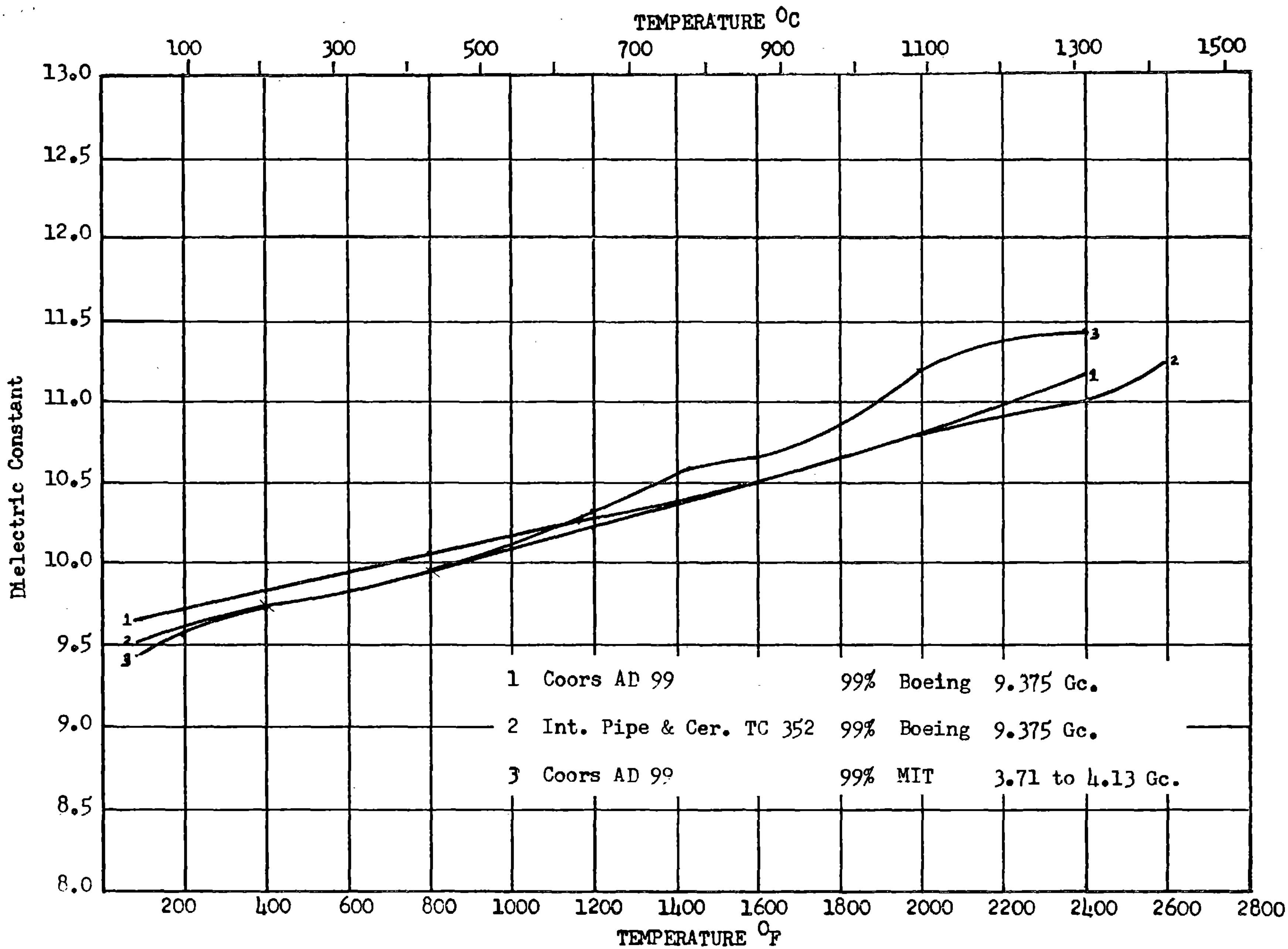

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
Dielectric Constant
13.0
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
1 Coors AD 99 99% Boeing 9.375 Gc.
2 Int. Pipe & Cer. TC 352 99% Boeing 9.375 Gc.
3 Coors AD 99 99% MIT 3.71 to 4.13 Gc.
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 25

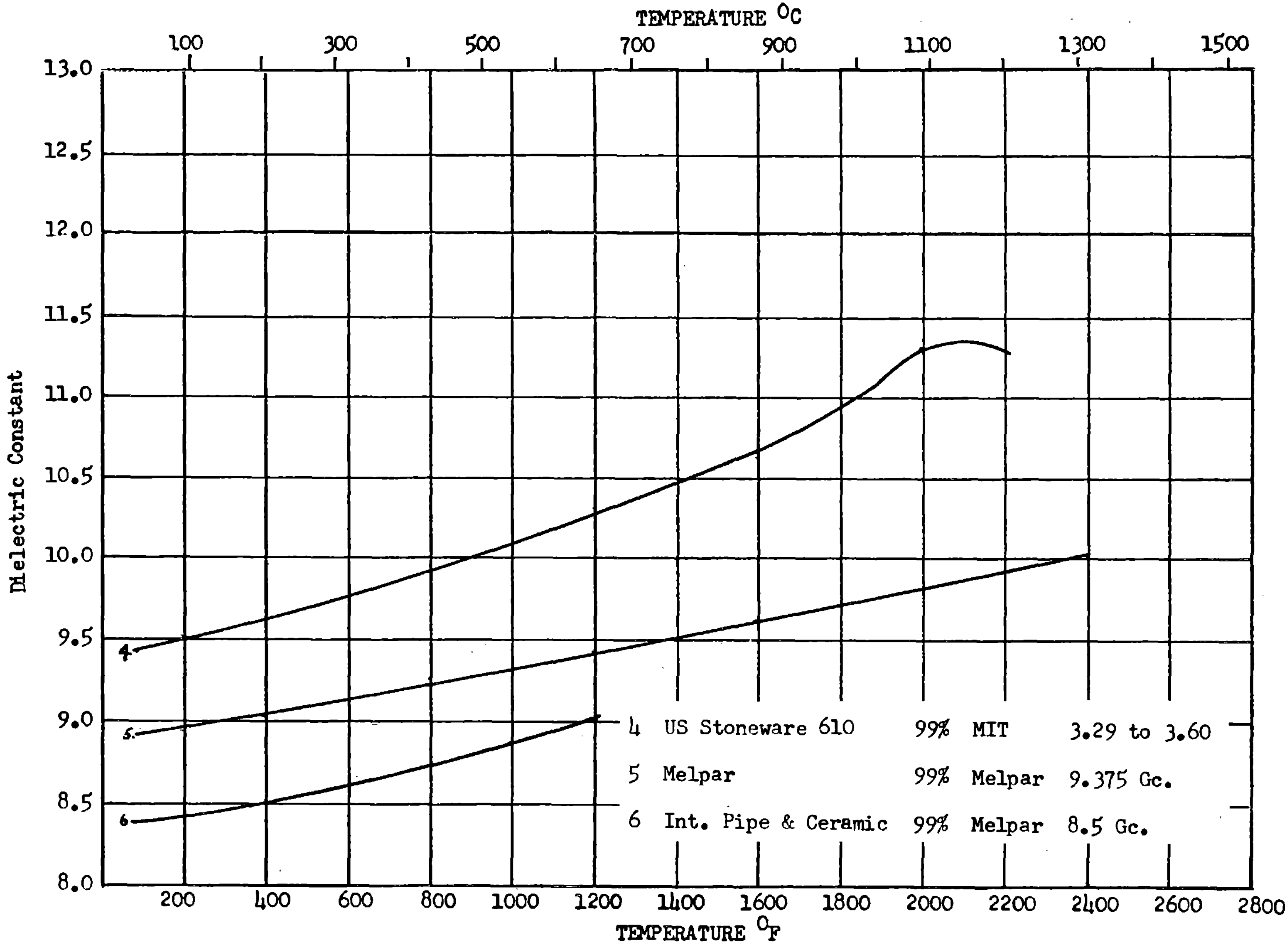

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
13.0
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
Dielectric Constant
4
5
6
4 US Stoneware 610 99% MIT 3.29 to 3.60
5 Melpar 99% Melpar 9.375 Gc.
6 Int. Pipe & Ceramic 99% Melpar 8.5 Gc.
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 26

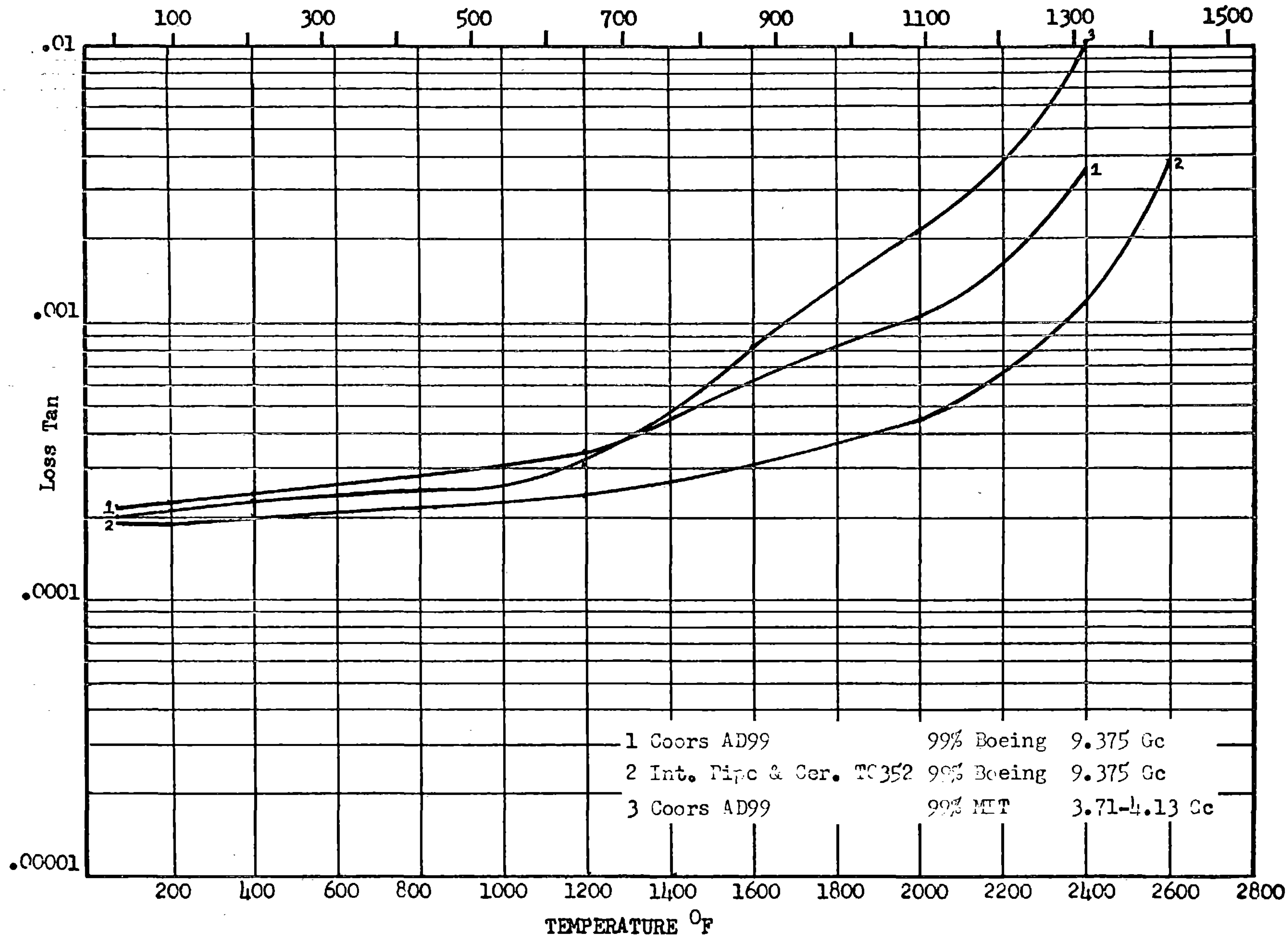

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.01
.001
.0001
.00001
Loss Tan
1 Coors AD99 99% Boeing 9.375 Gc
2 Int. Pipe & Cer. TC352 99% Boeing 9.375 Gc
3 Coors AD99 99% MIT 3.71-4.13 Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 27

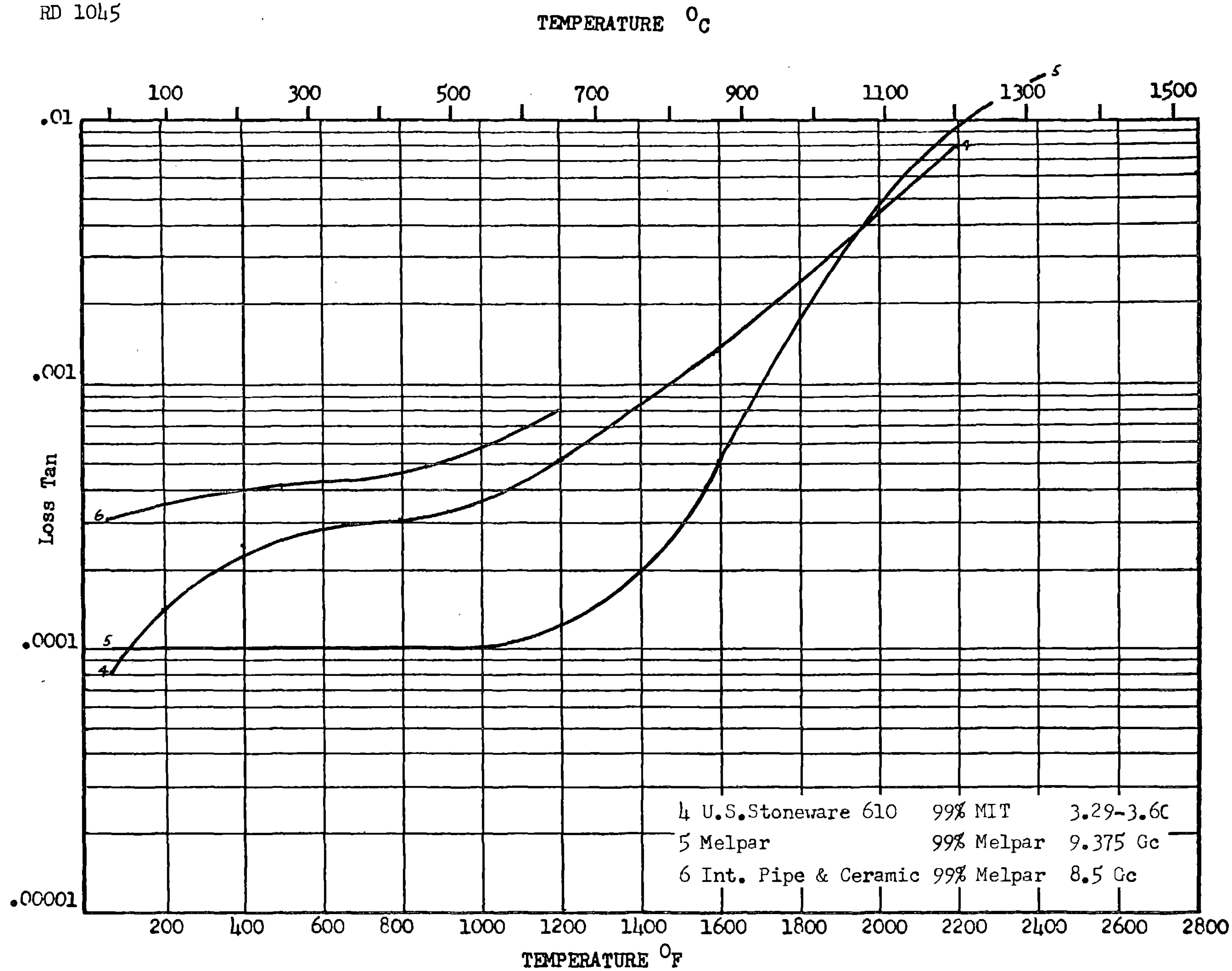

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.01
.001
.0001
.00001
Loss Tan
6
5
4
5
4 U.S.Stoneware 610 99% MIT 3.29-3.6C
5 Melpar 99% Melpar 9.375 Gc
6 Int. Pipe & Ceramic 99% Melpar 8.5 Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 28

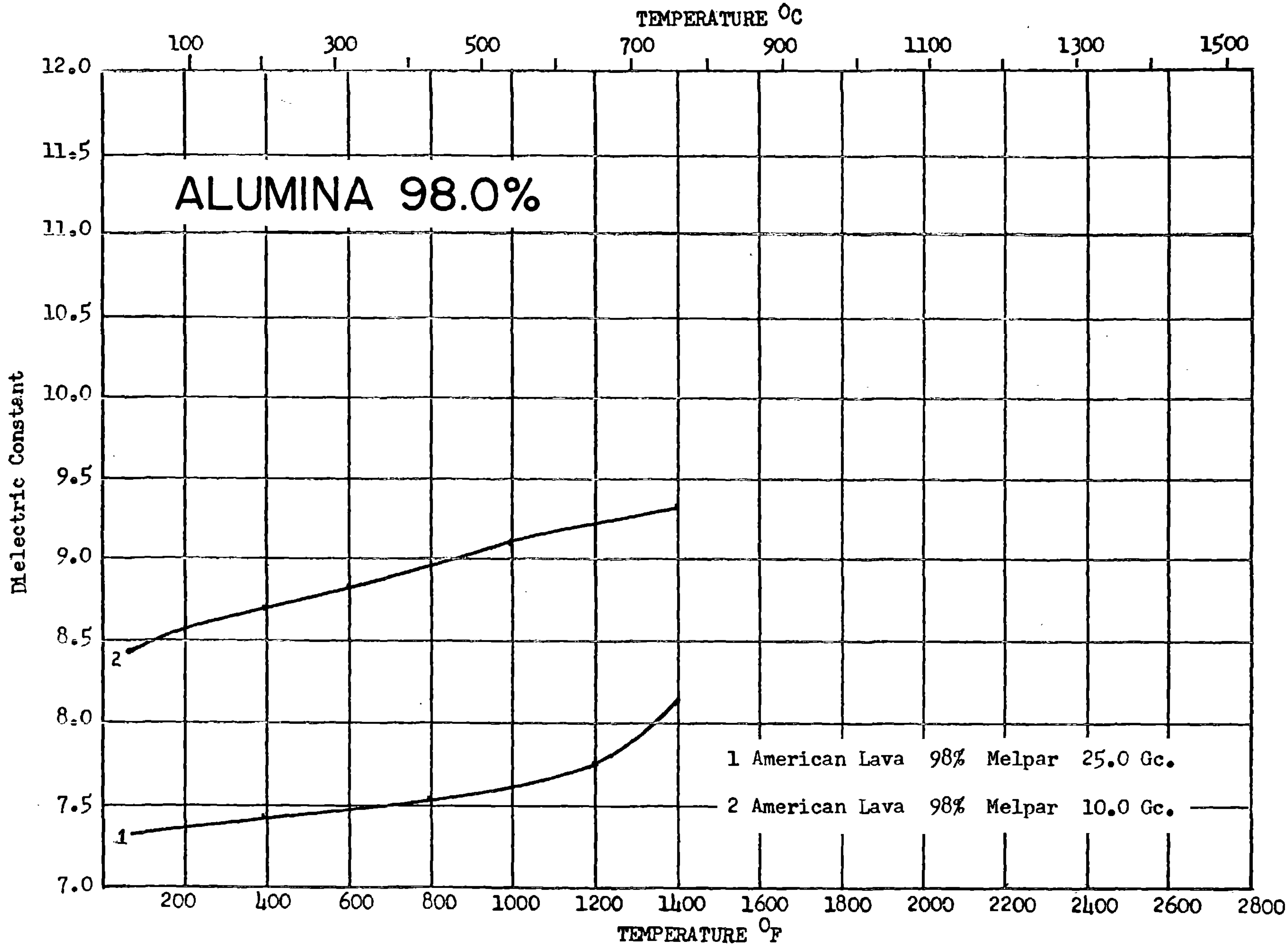

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
ALUMINA 98.0%
Dielectric Constant
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
2
1
1 American Lava 98% Melpar 25.0 Gc.
2 American Lava 98% Melpar 10.0 Gc.
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 29

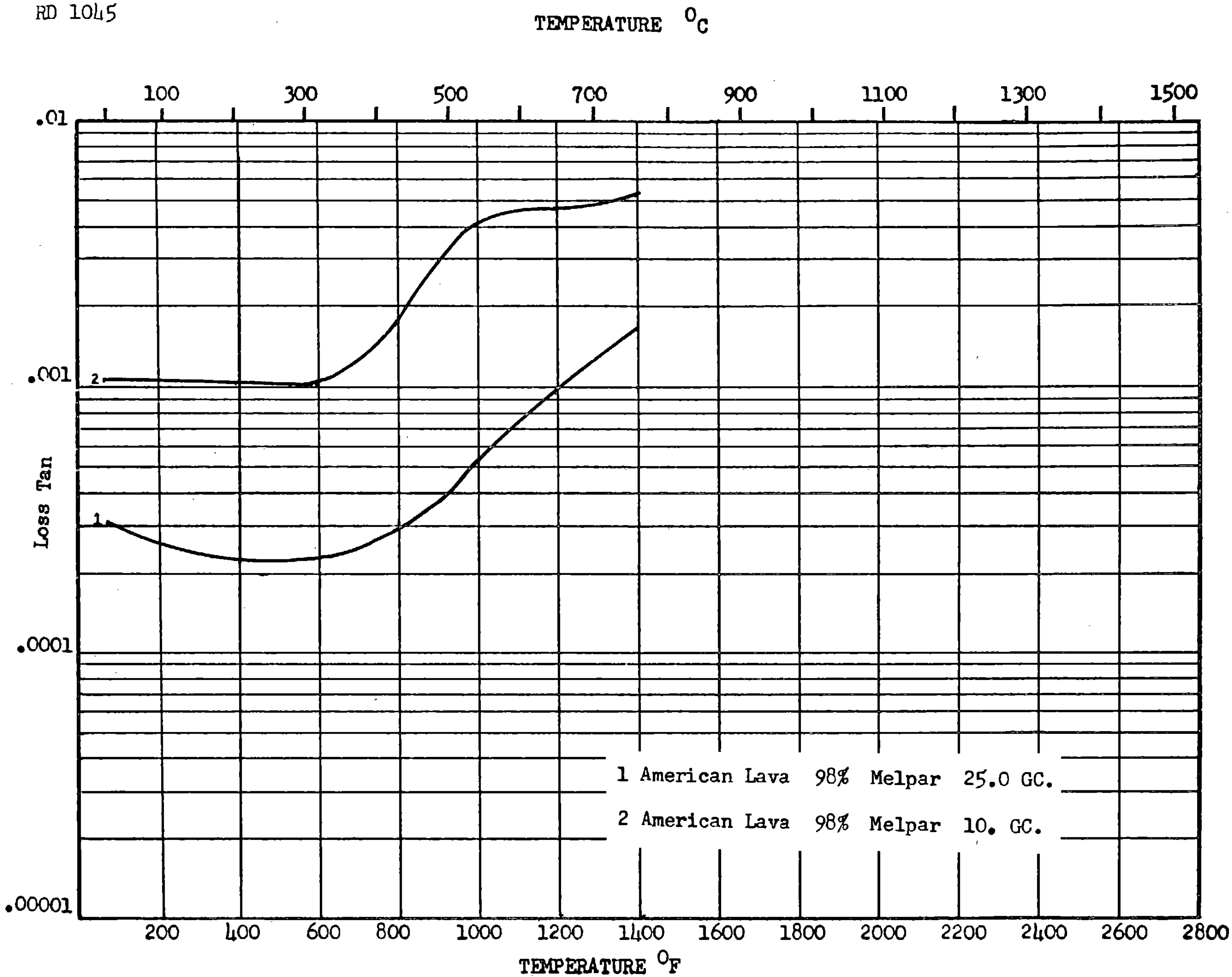

TEMPERATURE ^{O}C
100
300
500
700
900
1100
1300
1500
.01
.001
.0001
.00001
Loss Tan
1 American Lava 98% Melpar 25.0 GC.
2 American Lava 98% Melpar 10. GC.
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE ^{O}F

Figure 30

RD 1046

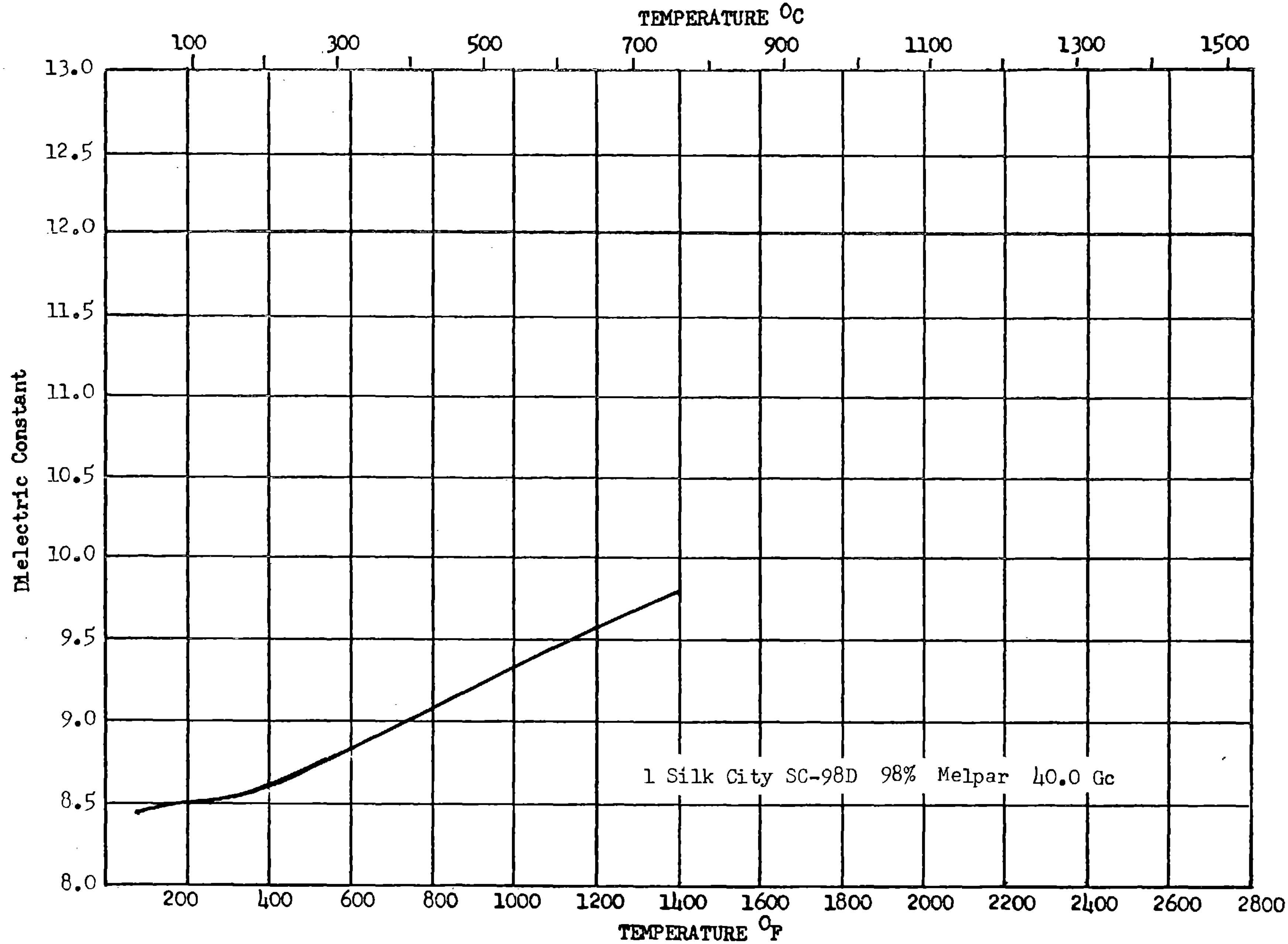


Figure 31

RD 1045

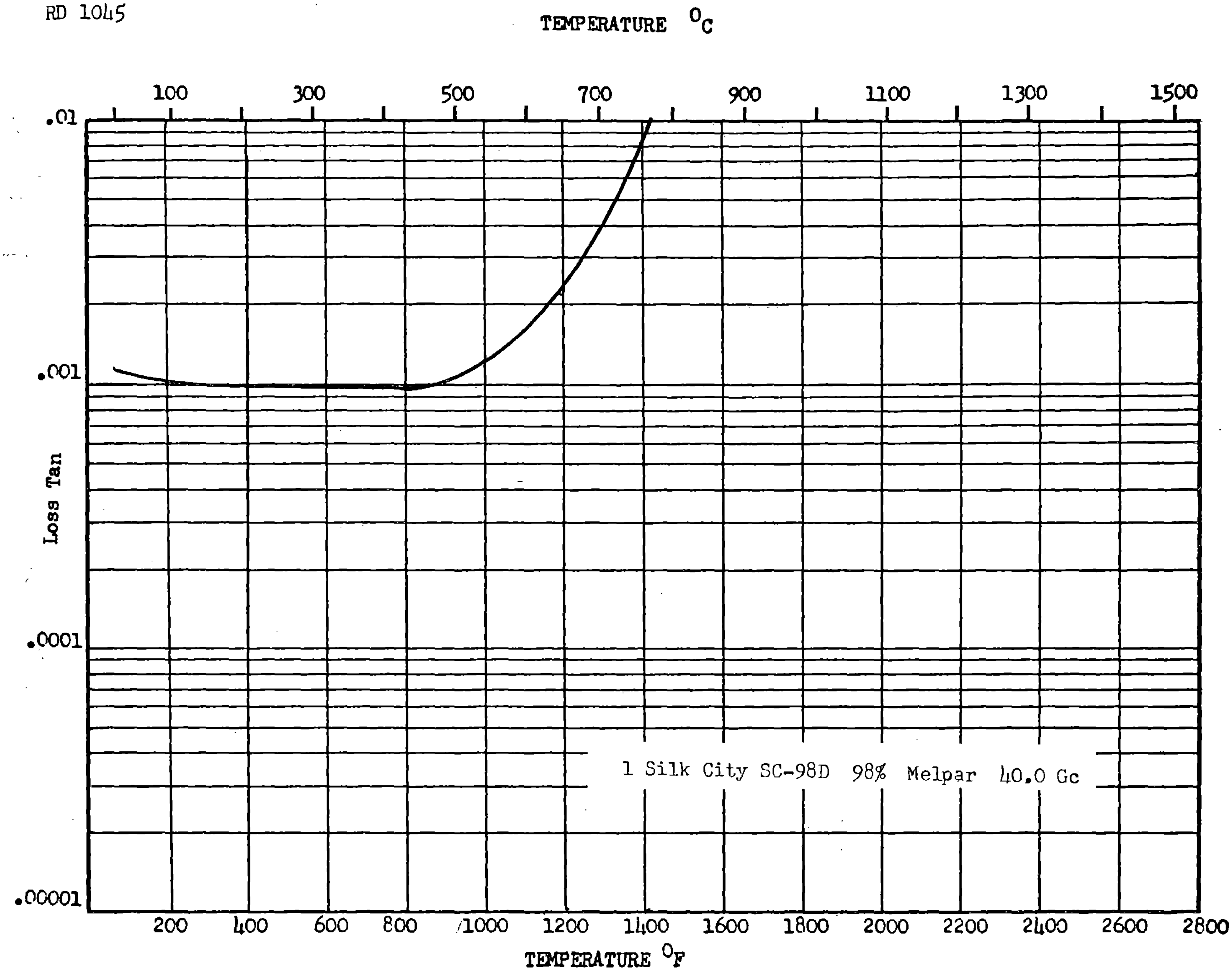


Figure 32

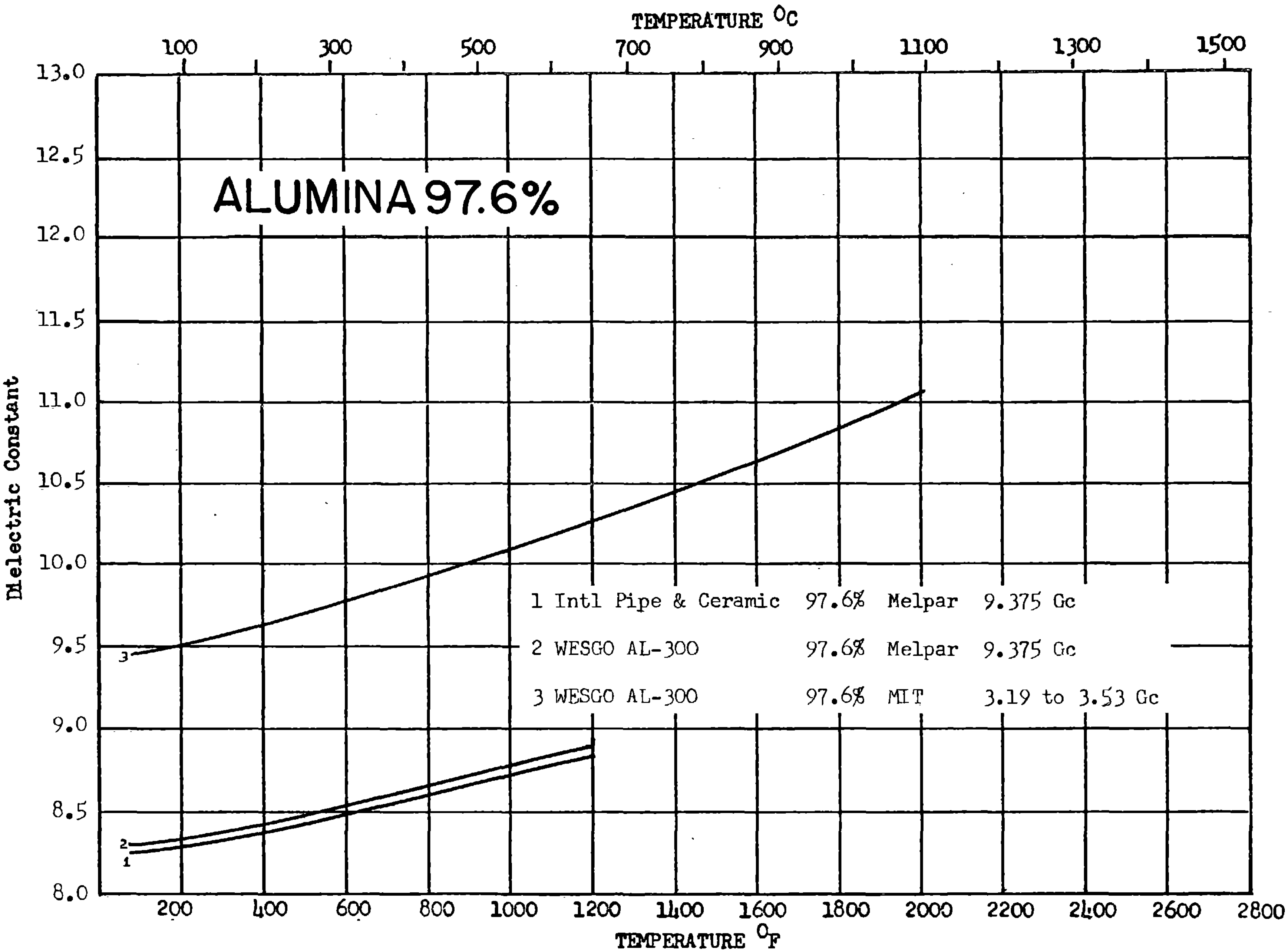

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
13.0
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
Dielectric Constant
ALUMINA 97.6%
1 Intl Pipe & Ceramic 97.6% Melpar 9.375 Gc
2 WESGO AL-300 97.6% Melpar 9.375 Gc
3 WESGO AL-300 97.6% MIT 3.19 to 3.53 Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 33

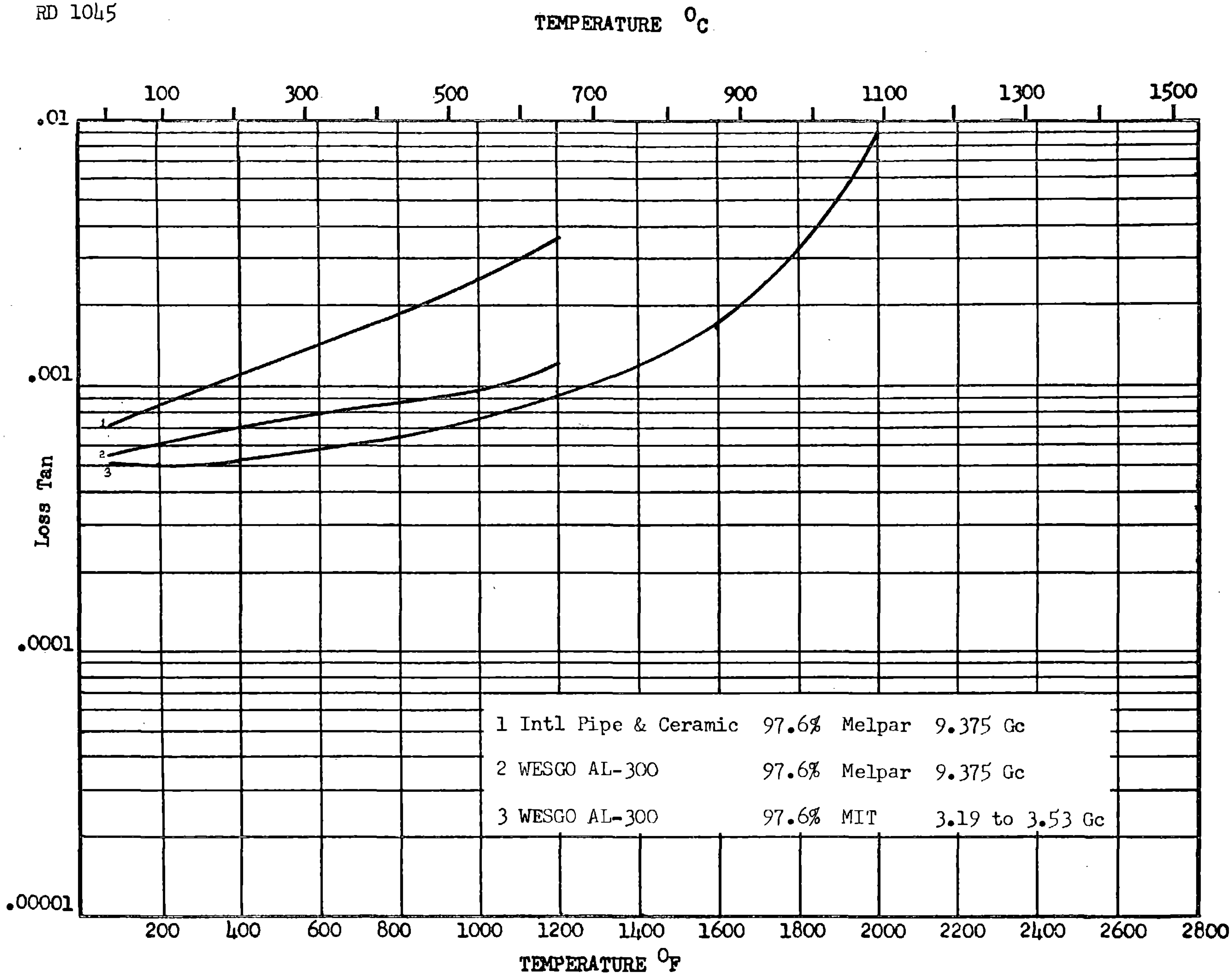

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.01
.001
.0001
.00001
Loss Tan
1
2
3
1 Intl Pipe & Ceramic 97.6% Melpar 9.375 Gc
2 WESGO AL-300 97.6% Melpar 9.375 Gc
3 WESGO AL-300 97.6% MIT 3.19 to 3.53 Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 34

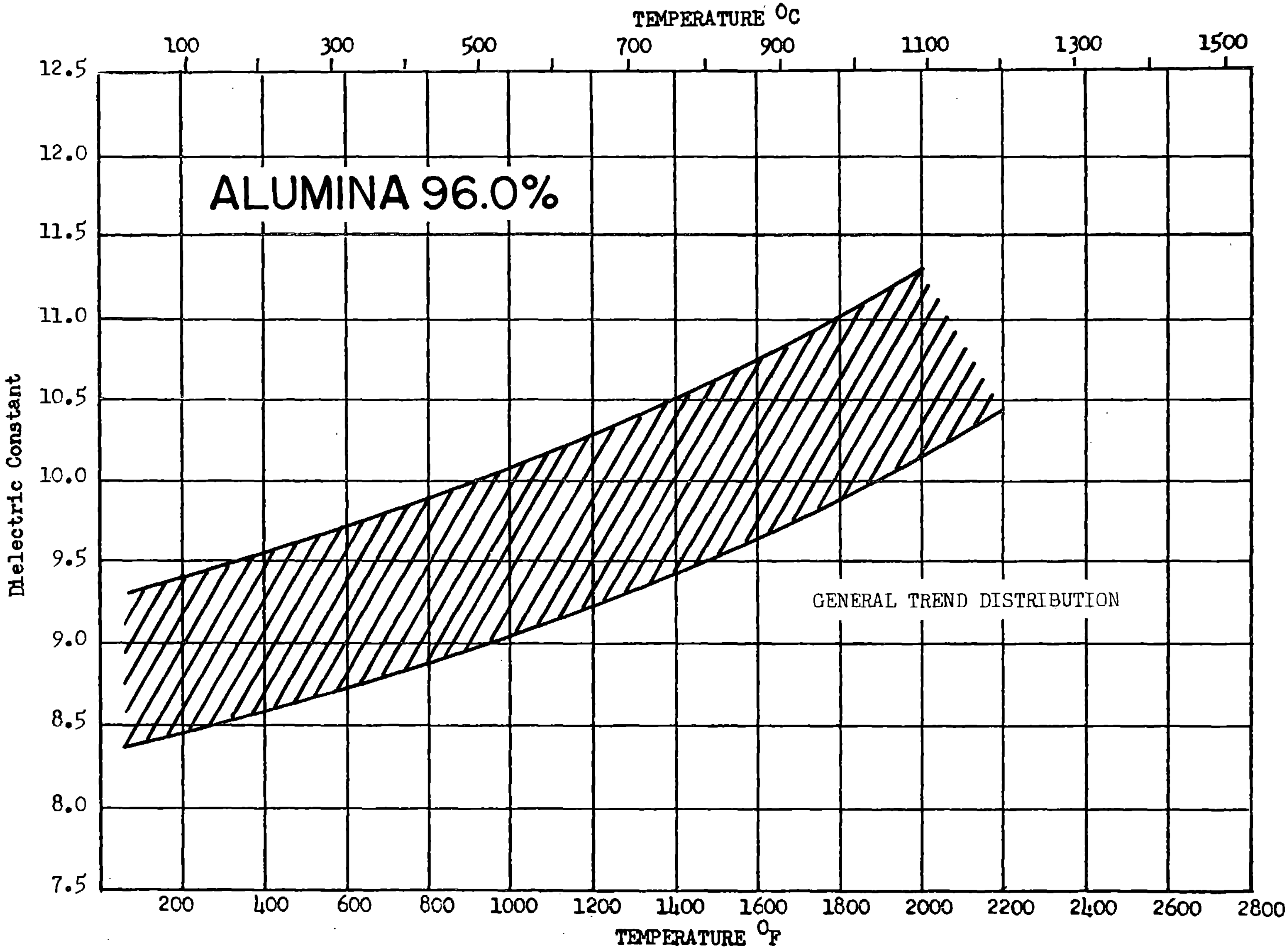

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
ALUMINA 96.0%
Dielectric Constant
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
GENERAL TREND DISTRIBUTION
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 35

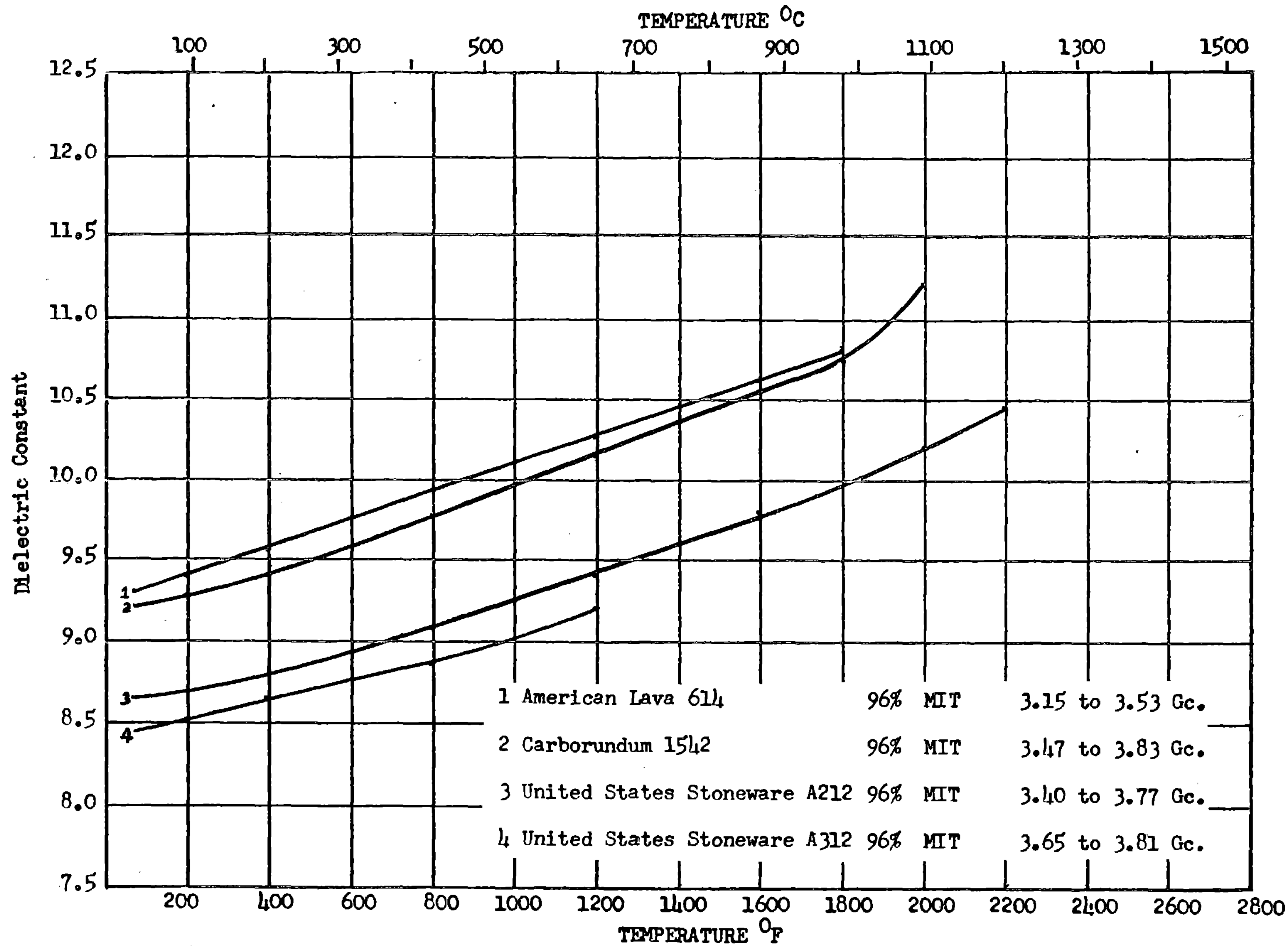

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
Dielectric Constant
1
2
3
4
1 American Lava 614 96% MIT 3.15 to 3.53 Gc.
2 Carborundum 1542 96% MIT 3.47 to 3.83 Gc.
3 United States Stoneware A212 96% MIT 3.40 to 3.77 Gc.
4 United States Stoneware A312 96% MIT 3.65 to 3.81 Gc.
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 36

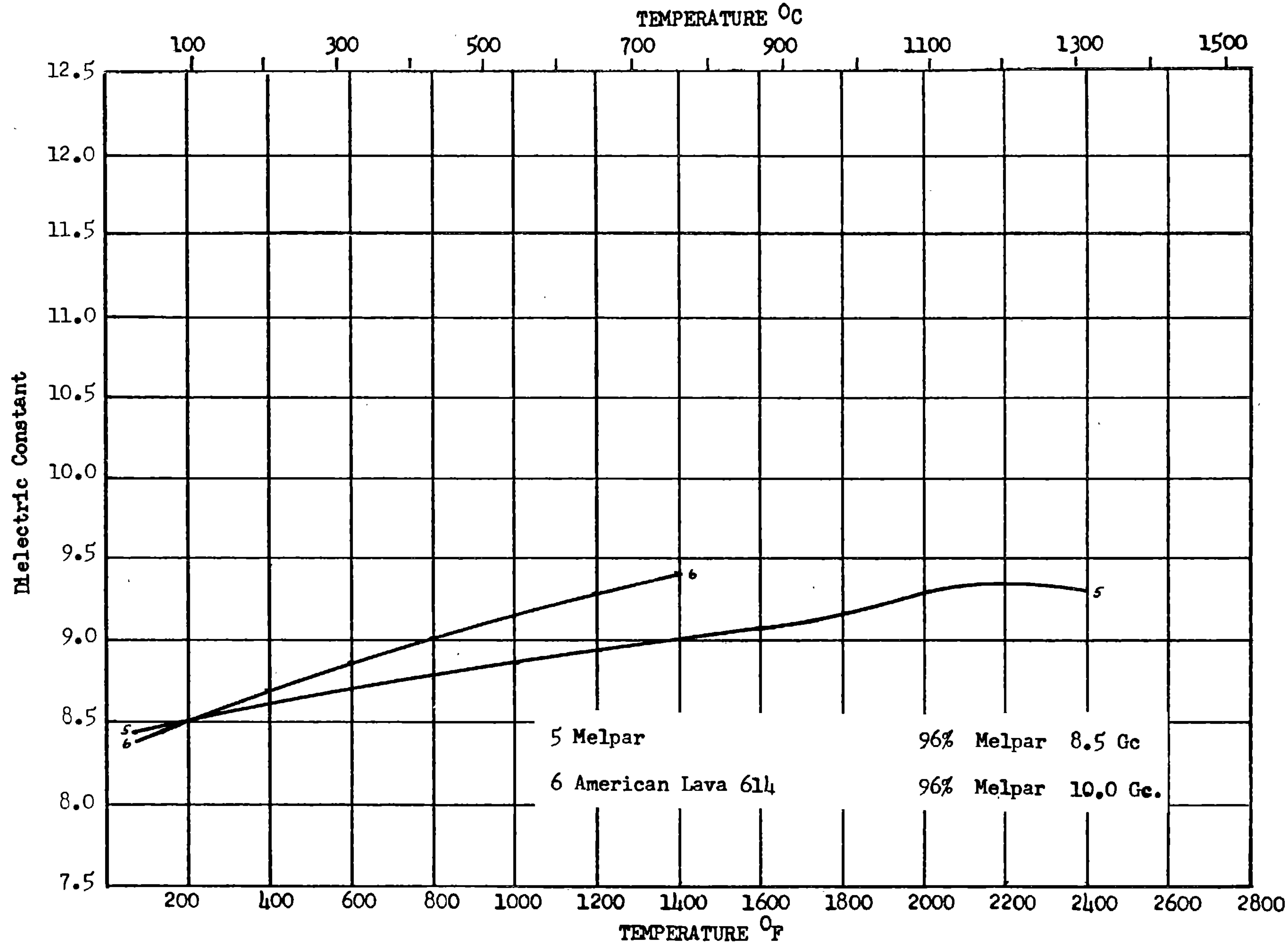

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
Dielectric Constant
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F
5 Melpar
6 American Lava 614
96% Melpar 8.5 Gc
96% Melpar 10.0 Gc.
5
6

Figure 37

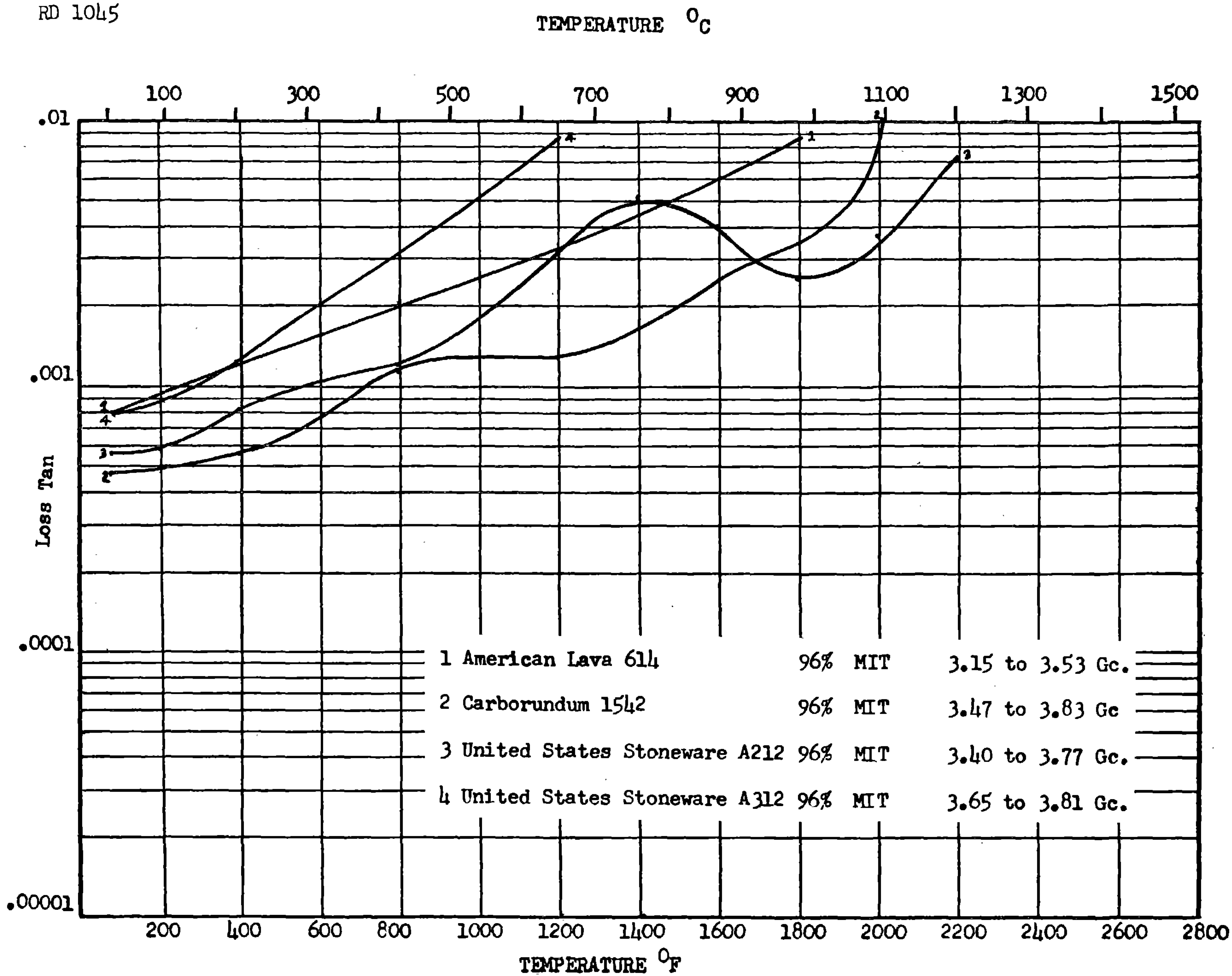

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.01
.001
.0001
.00001
Loss Tan
1
2
3
4
1 American Lava 614 96% MIT 3.15 to 3.53 Gc.
2 Carborundum 1542 96% MIT 3.47 to 3.83 Gc
3 United States Stoneware A212 96% MIT 3.40 to 3.77 Gc.
4 United States Stoneware A312 96% MIT 3.65 to 3.81 Gc.
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 38

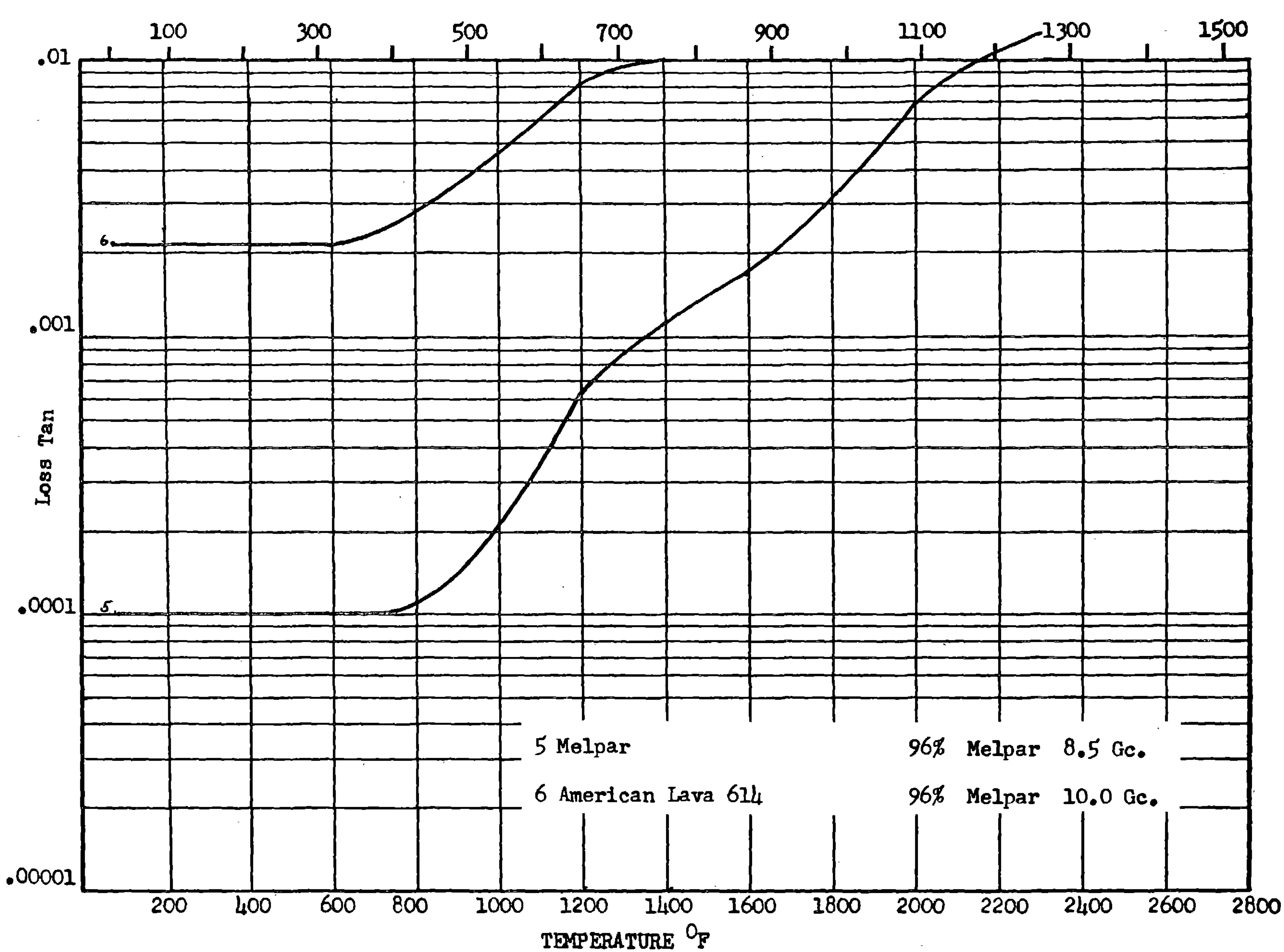

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.01
.001
.0001
.00001
Loss Tan
6
5
5 Melpar
6 American Lava 614
96% Melpar 8.5 Gc.
96% Melpar 10.0 Gc.
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 39

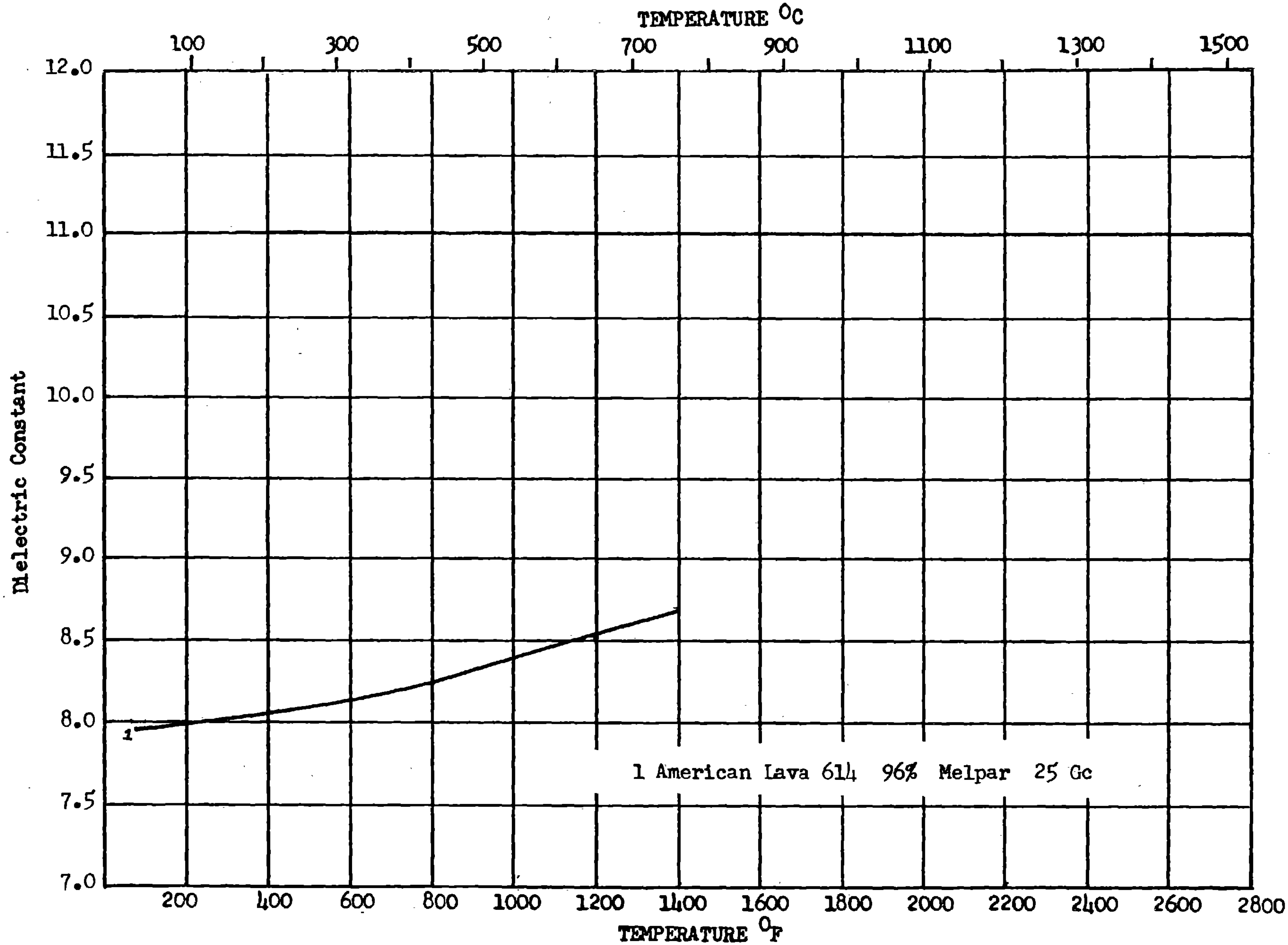

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
Dielectric Constant
1
1 American Lava 614 96% Melpar 25 Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 40

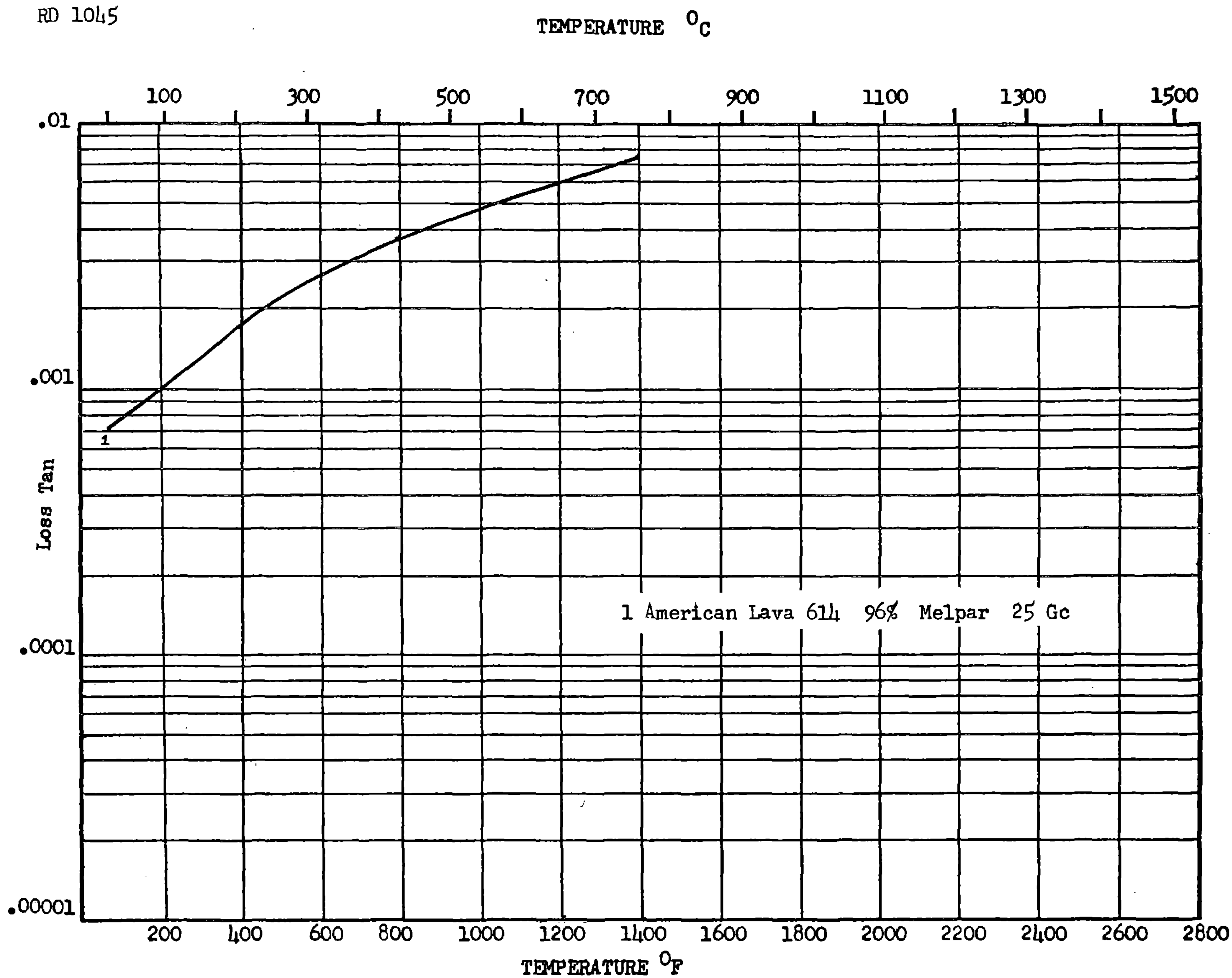

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.01
.001
.0001
.00001
Loss Tan
1
1 American Lava 614 96% Melpar 25 Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 41

RD 1046

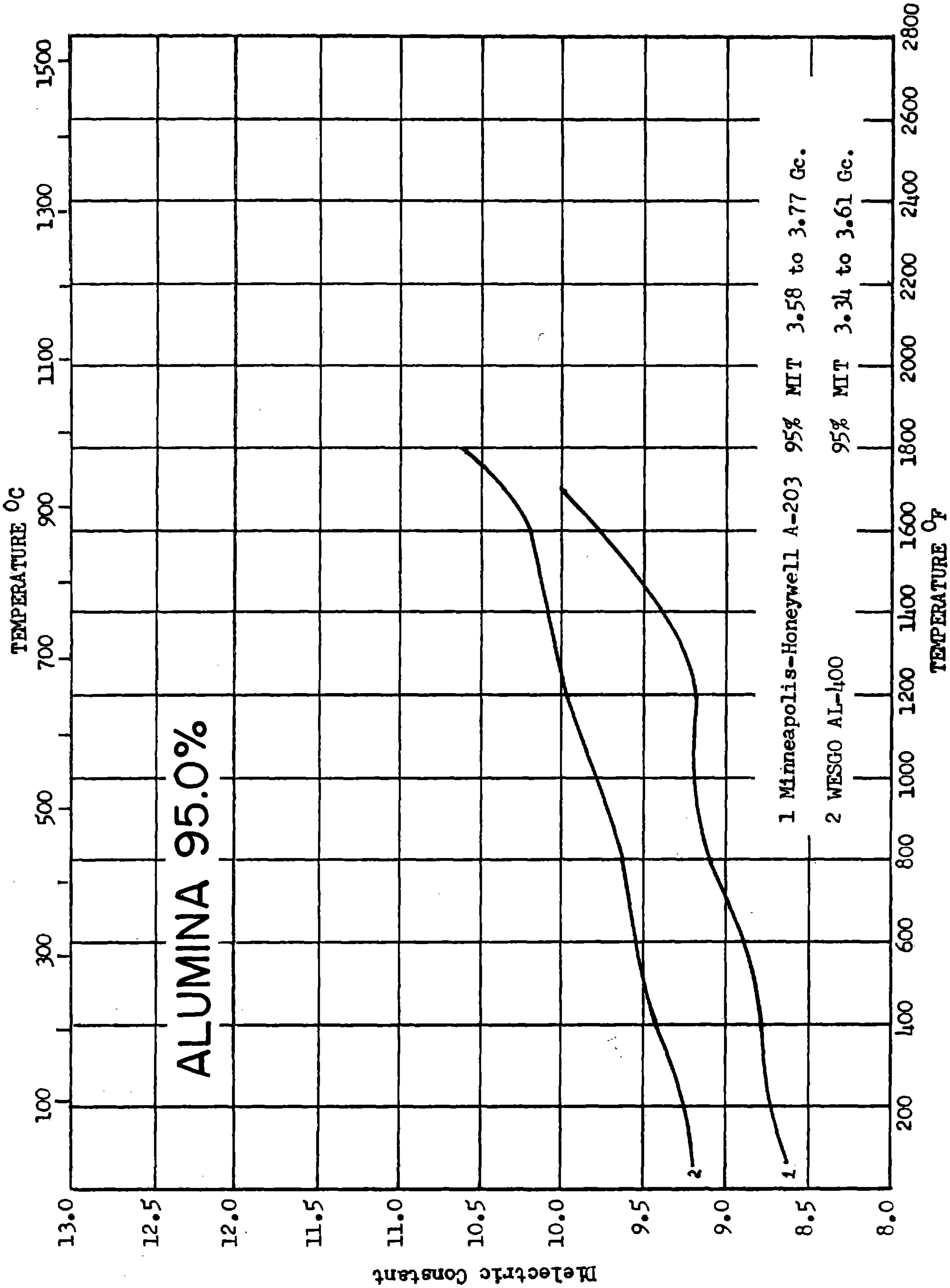


Figure 42

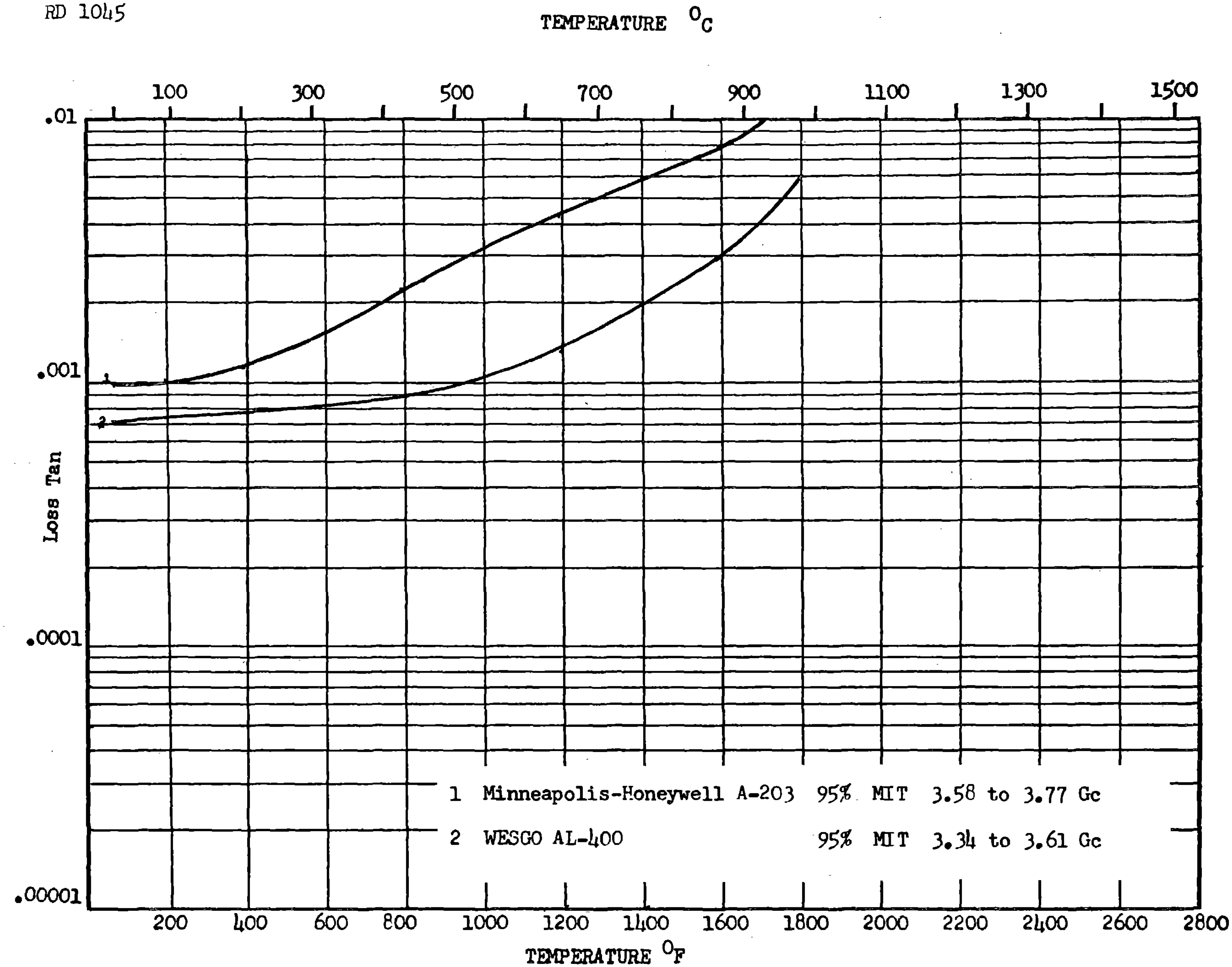

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.01
.001
.0001
.00001
Loss Tan
1 Minneapolis-Honeywell A-203 95% MIT 3.58 to 3.77 Gc
2 WESGO AL-400 95% MIT 3.34 to 3.61 Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 43

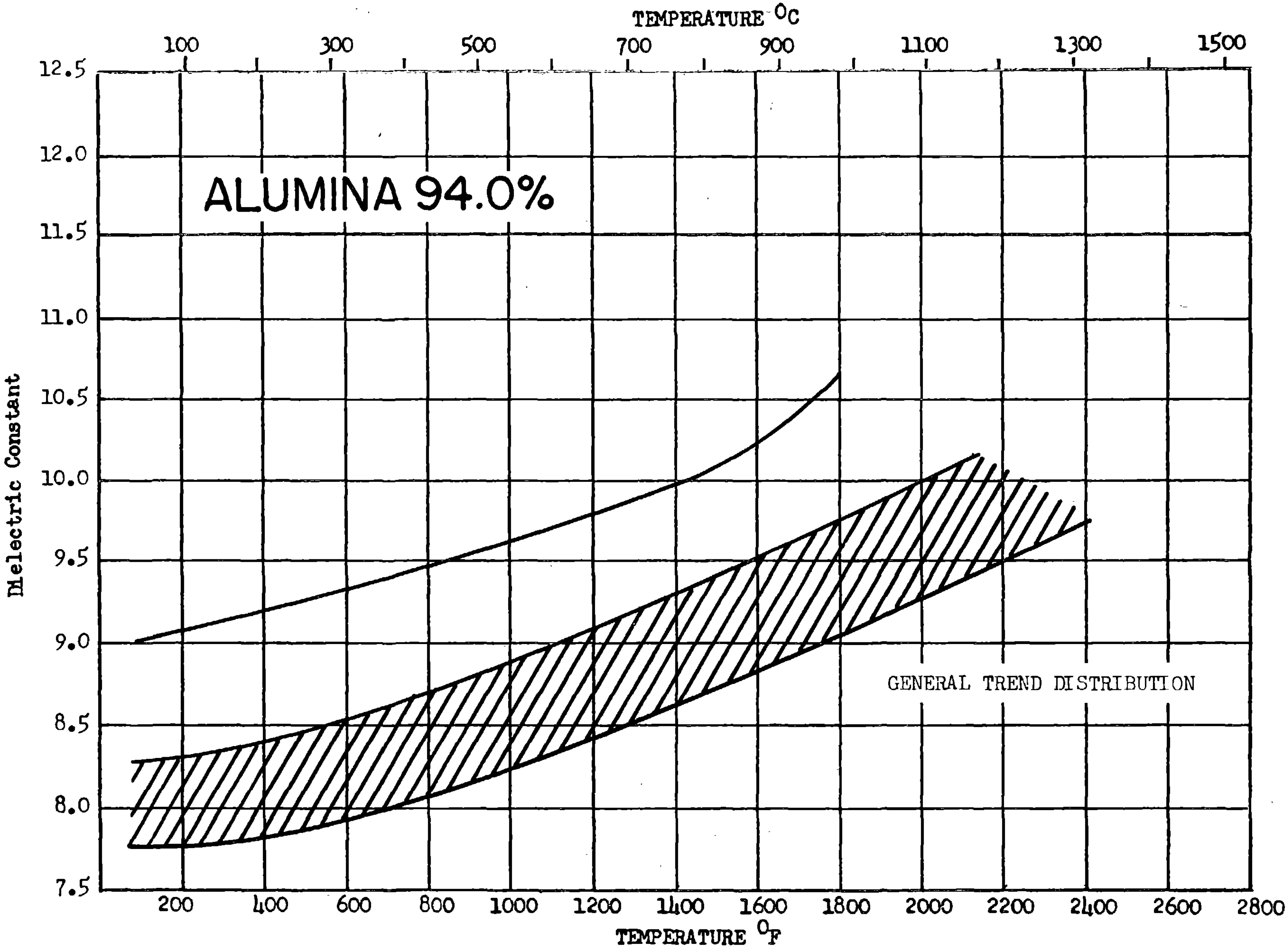

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
Dielectric Constant
ALUMINA 94.0%
GENERAL TREND DISTRIBUTION
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 44

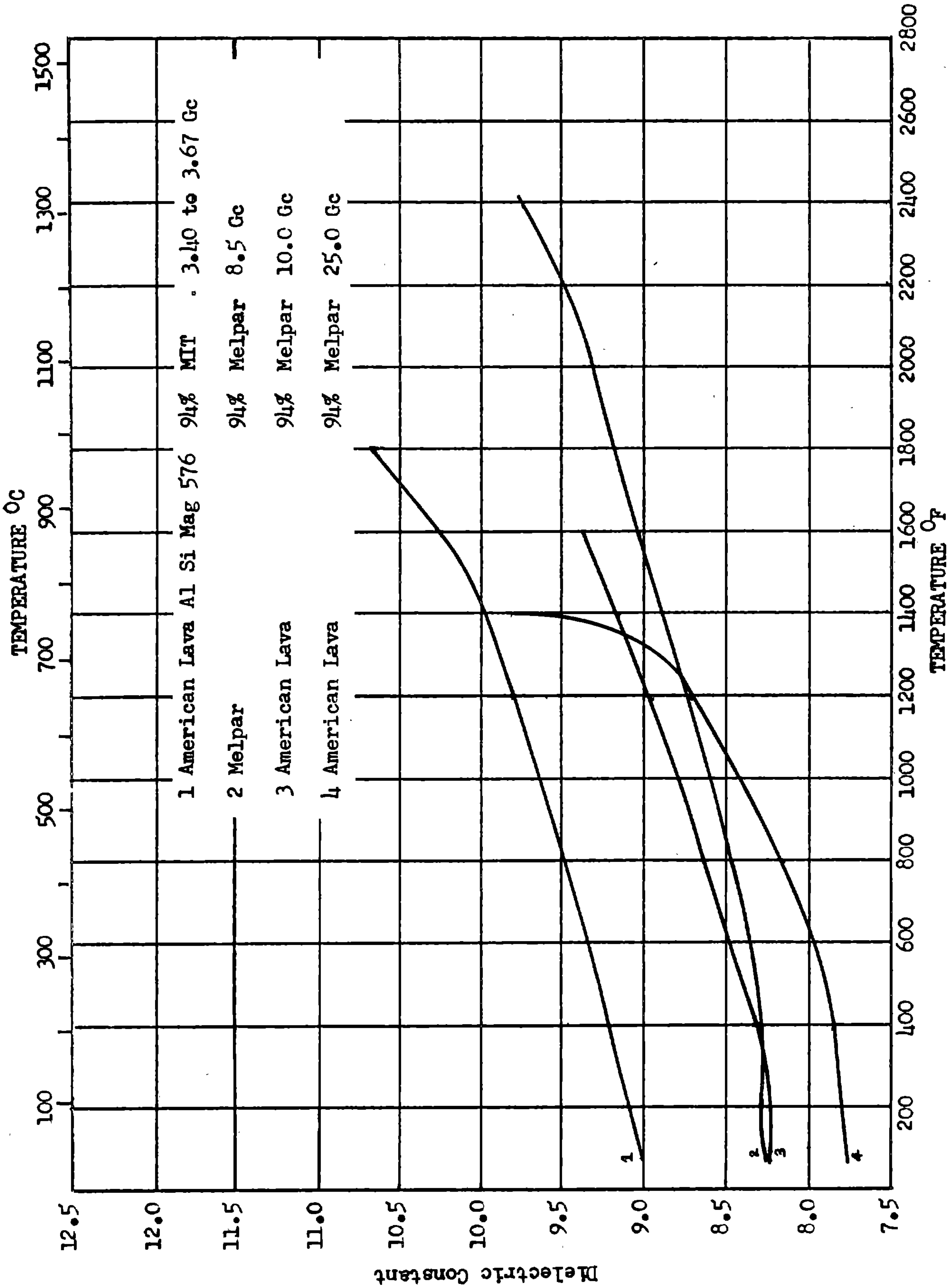

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
1 American Lava Al Si Mag 576 94% MIT . 3.40 to 3.67 Gc
2 Melpar 94% Melpar 8.5 Gc
3 American Lava 94% Melpar 10.0 Gc
4 American Lava 94% Melpar 25.0 Gc
1
2
3
4
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
Dielectric Constant
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 45

RD 1045

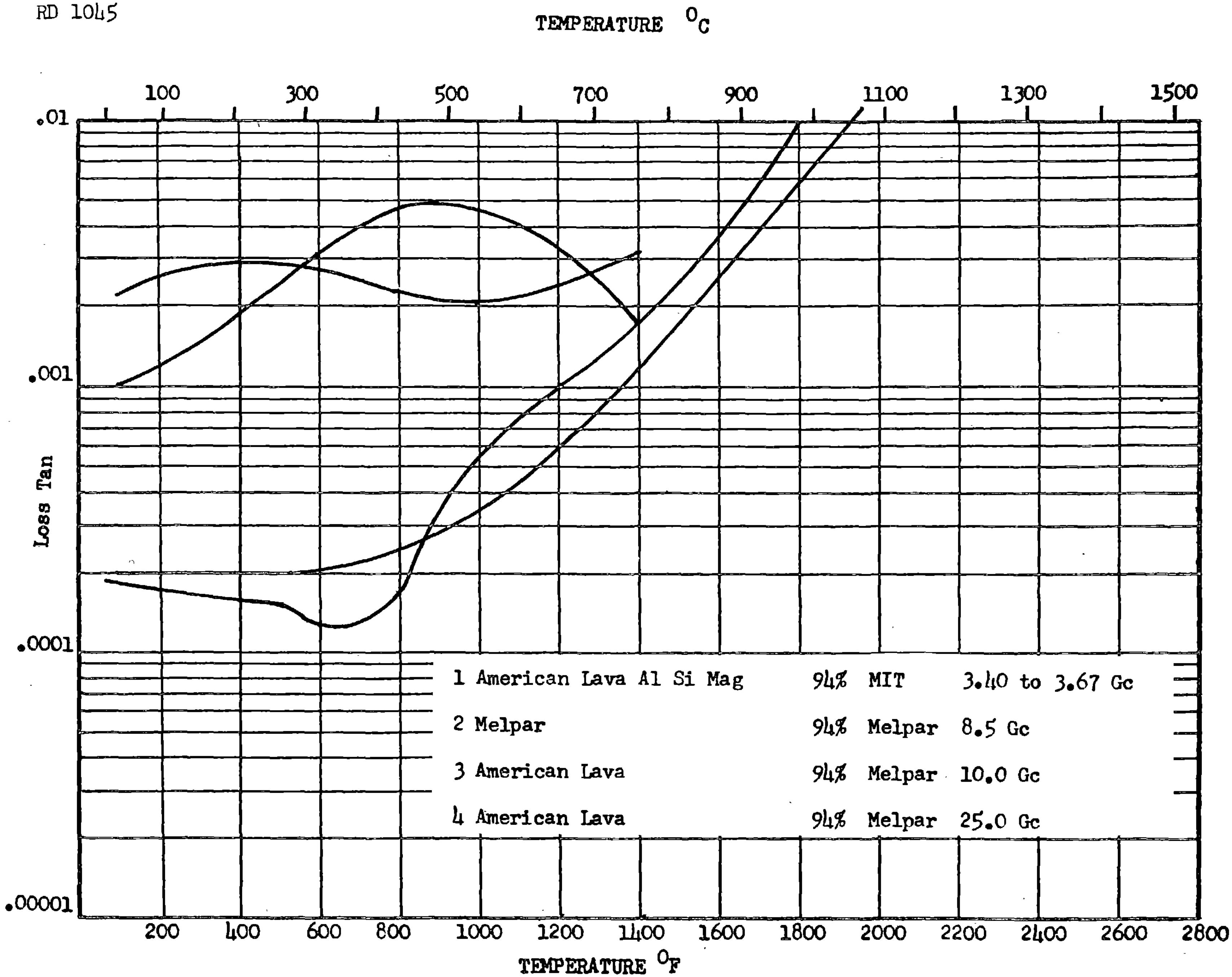


Figure 46

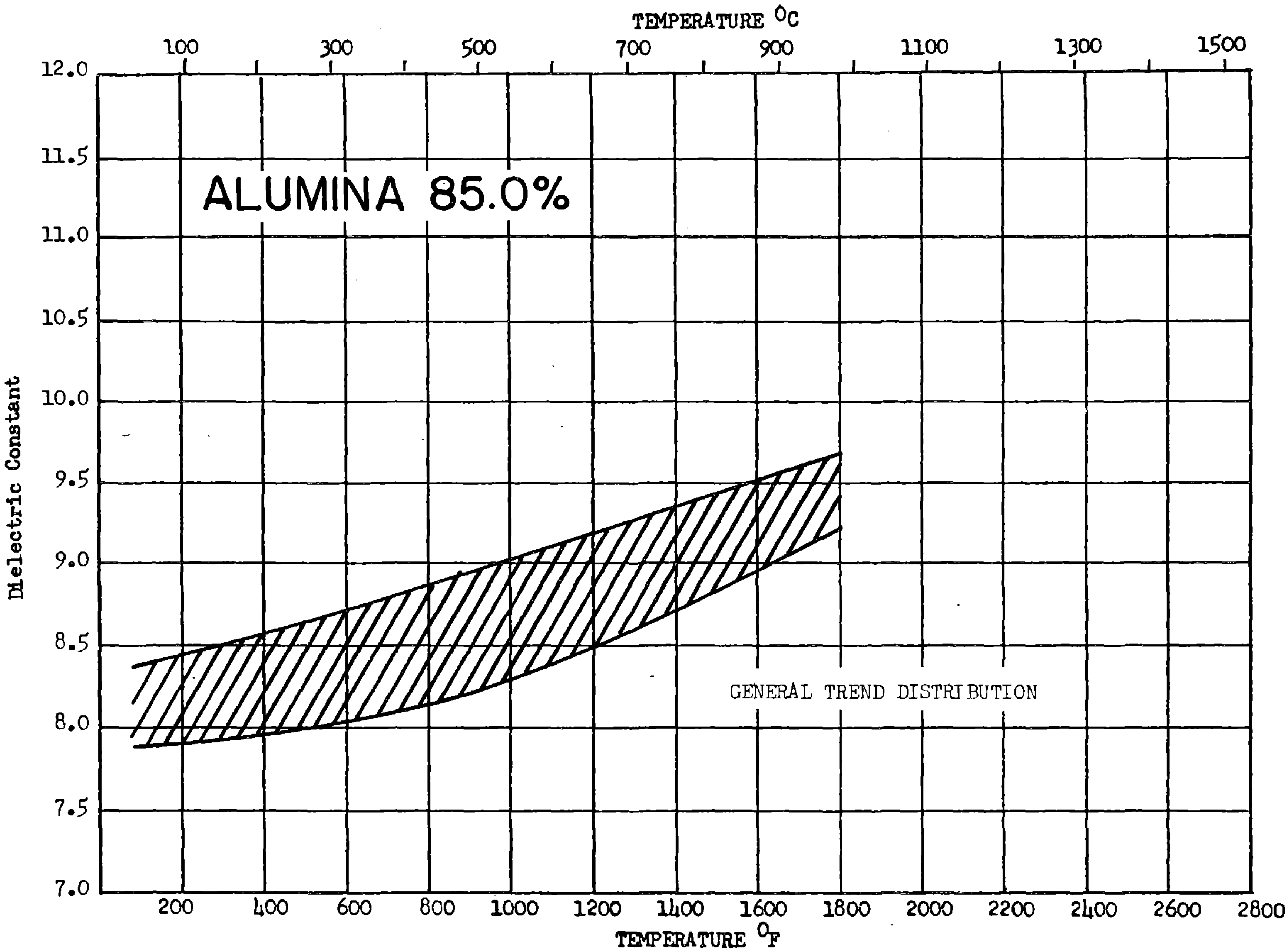

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
Dielectric Constant
ALUMINA 85.0%
GENERAL TREND DISTRIBUTION
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 47

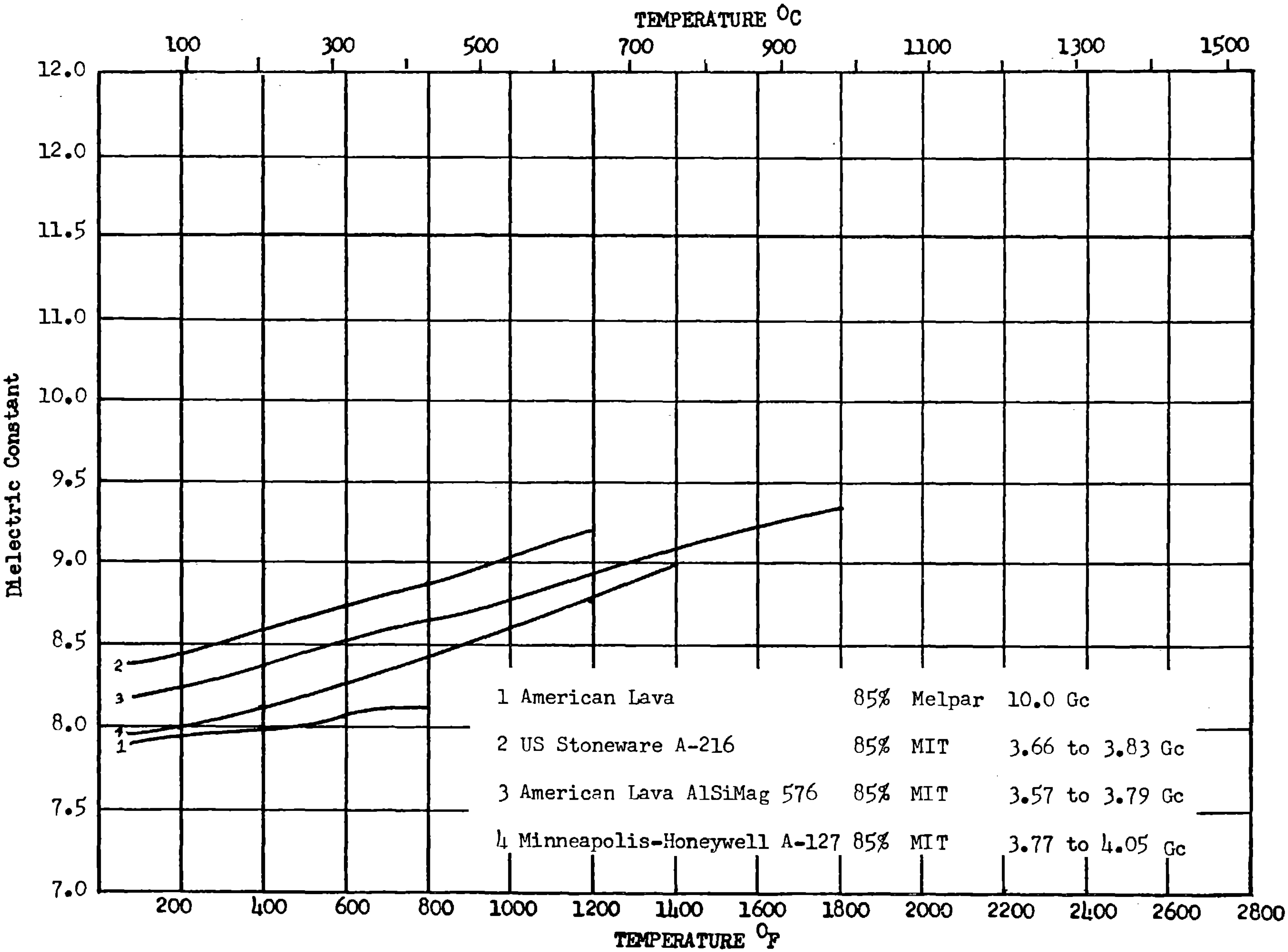

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
Dielectric Constant
12.0
12.0
11.5
11.0
10.0
9.5
9.0
8.5
8.0
7.5
7.0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F
1 American Lava 85% Melpar 10.0 Gc
2 US Stoneware A-216 85% MIT 3.66 to 3.83 Gc
3 American Lava AlSiMag 576 85% MIT 3.57 to 3.79 Gc
4 Minneapolis-Honeywell A-127 85% MIT 3.77 to 4.05 Gc
2
3
4
1

Figure 48

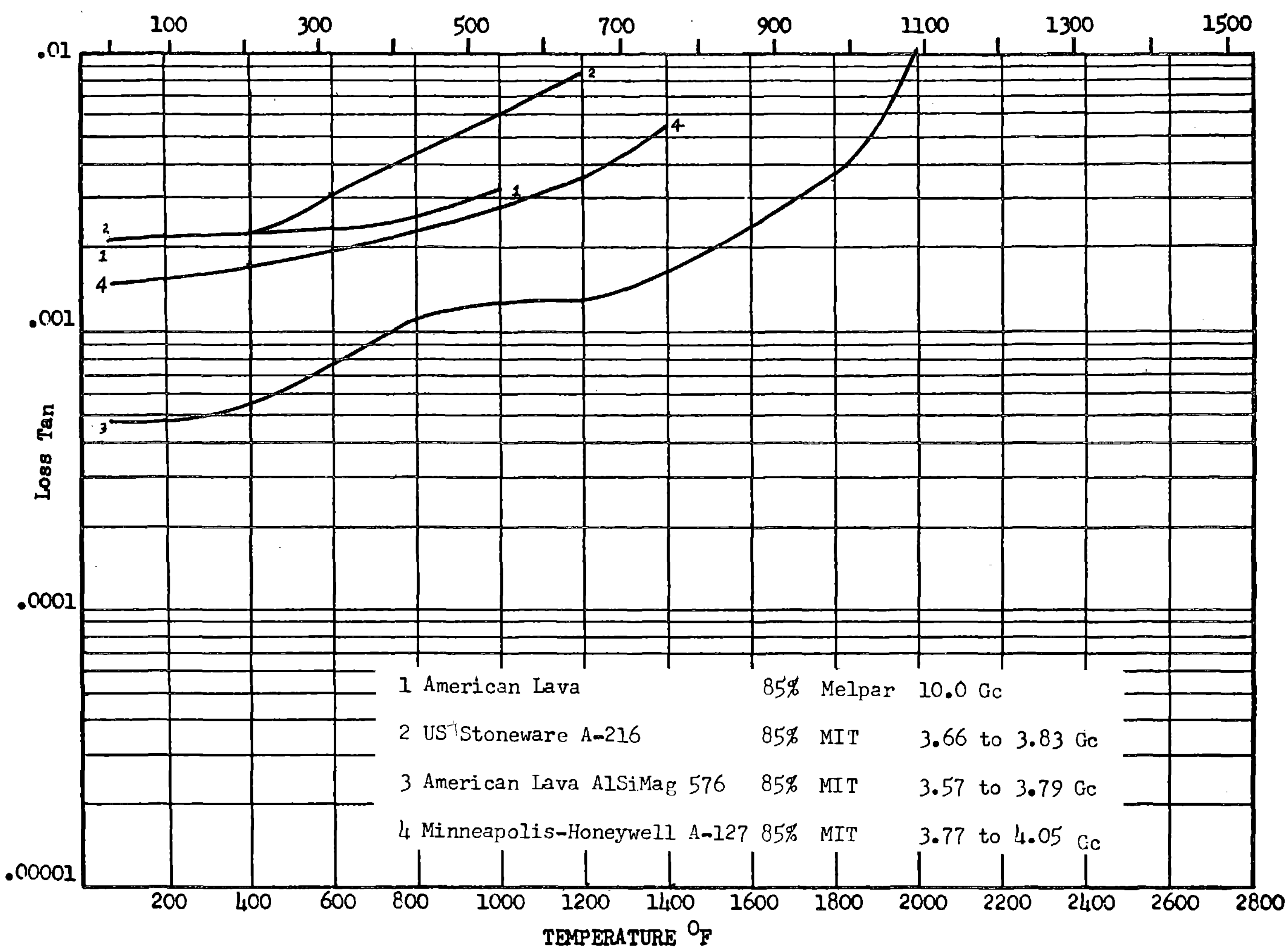

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.01
.001
.0001
.00001
Loss Tan
1
2
3
4
1 American Lava 85% Melpar 10.0 Gc
2 US Stoneware A-216 85% MIT 3.66 to 3.83 Gc
3 American Lava AlSiMag 576 85% MIT 3.57 to 3.79 Gc
4 Minneapolis-Honeywell A-127 85% MIT 3.77 to 4.05 Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 49

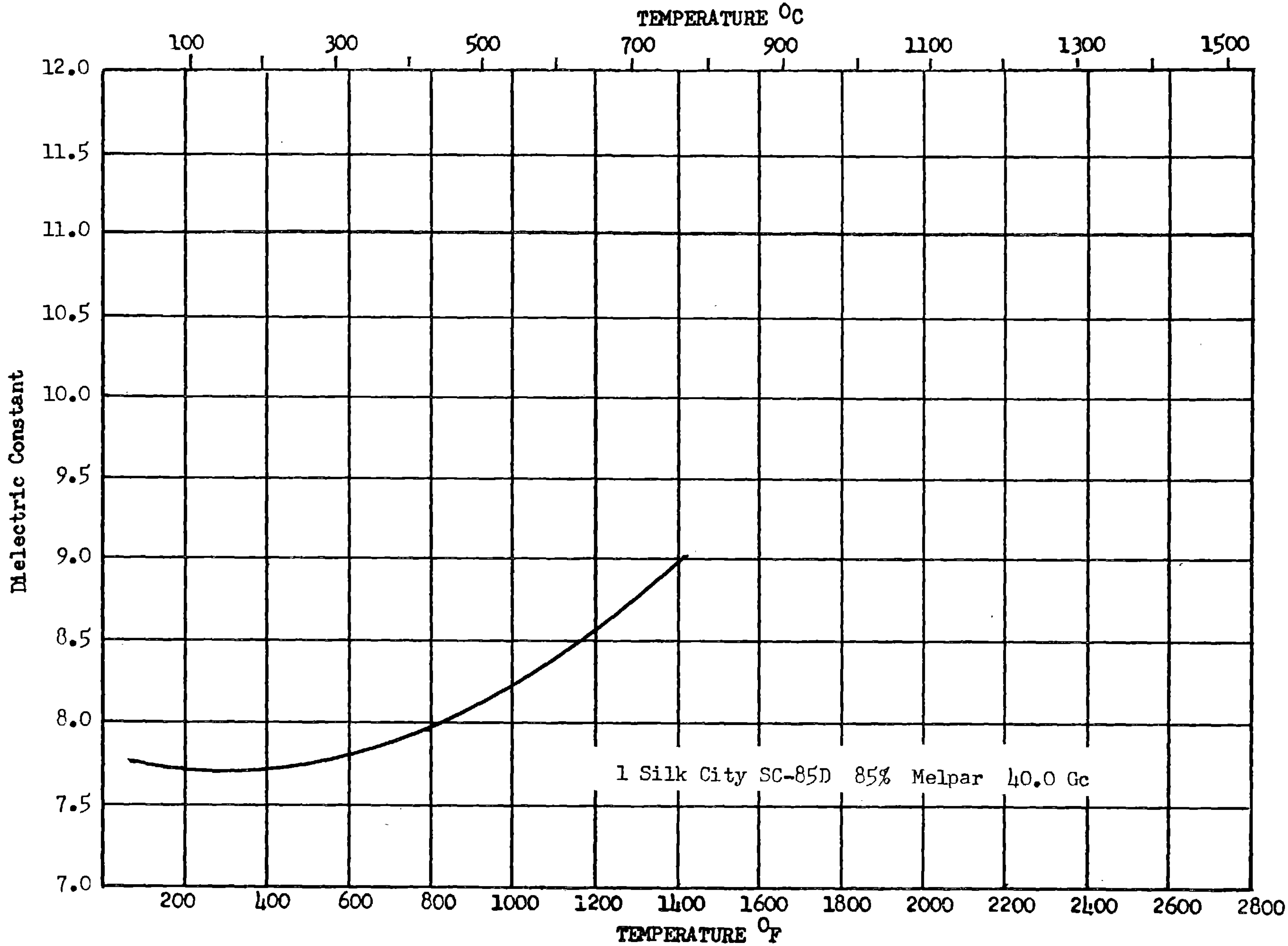

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
Dielectric Constant
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
1 Silk City SC-85D 85% Melpar 40.0 Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 50

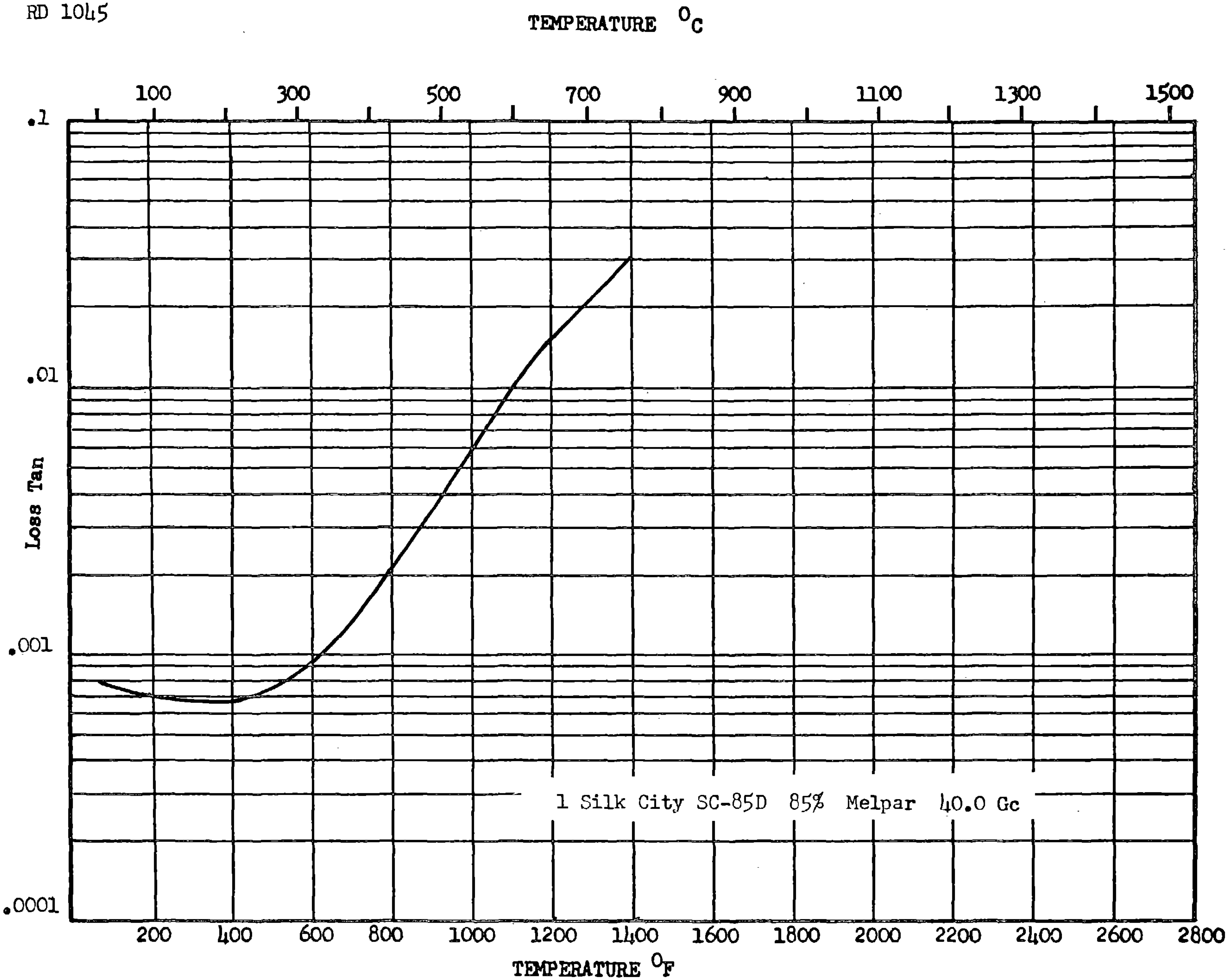

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.1
.01
.001
.0001
Loss Tan
1 Silk City SC-85D 85% Melpar 40.0 Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 51

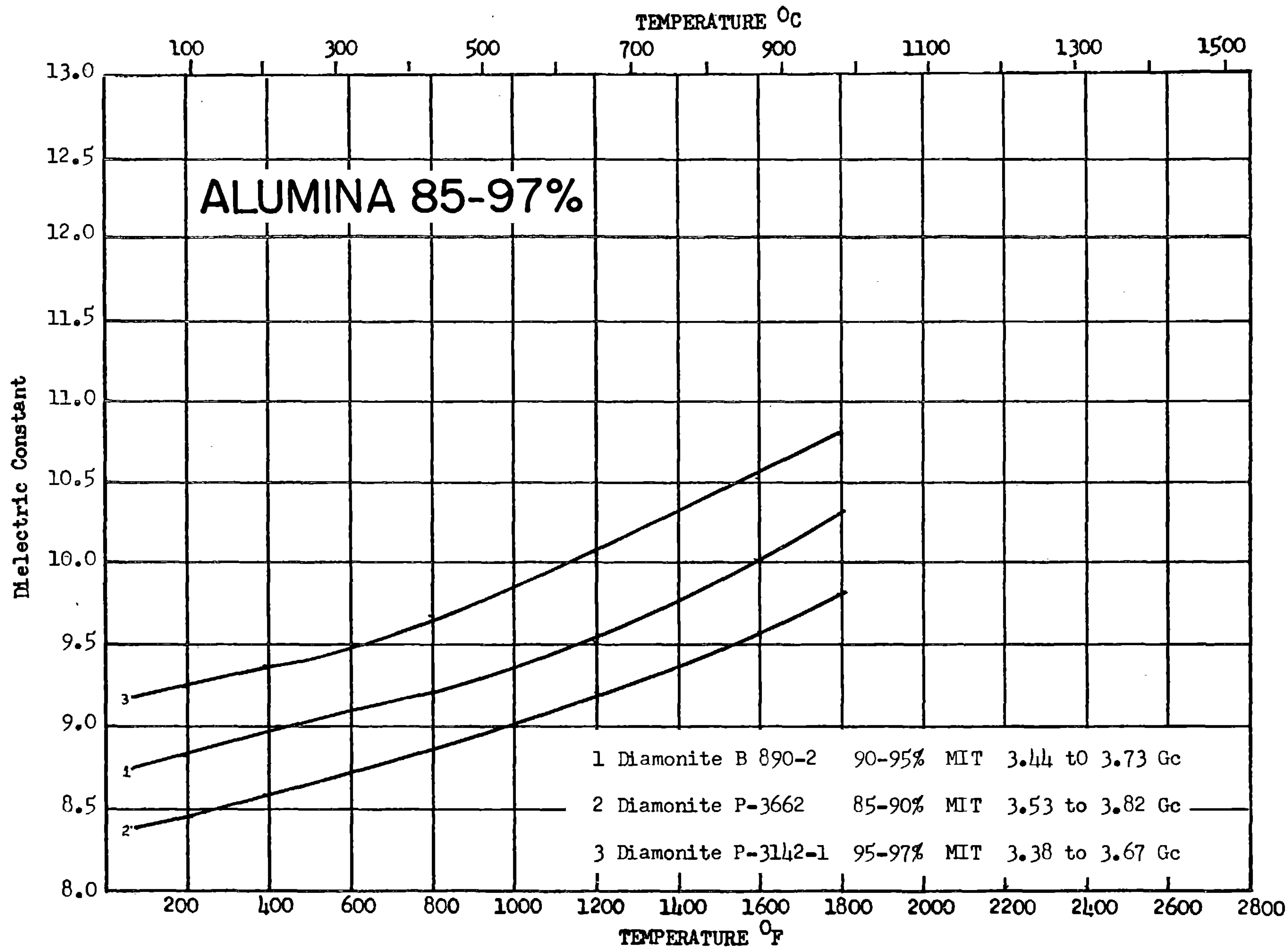

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
ALUMINA 85-97%
Dielectric Constant
13.0
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
3
1
2
1 Diamonite B 890-2 90-95% MIT 3.44 tO 3.73 Gc
2 Diamonite P-3662 85-90% MIT 3.53 to 3.82 Gc
3 Diamonite P-3142-1 95-97% MIT 3.38 to 3.67 Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 52

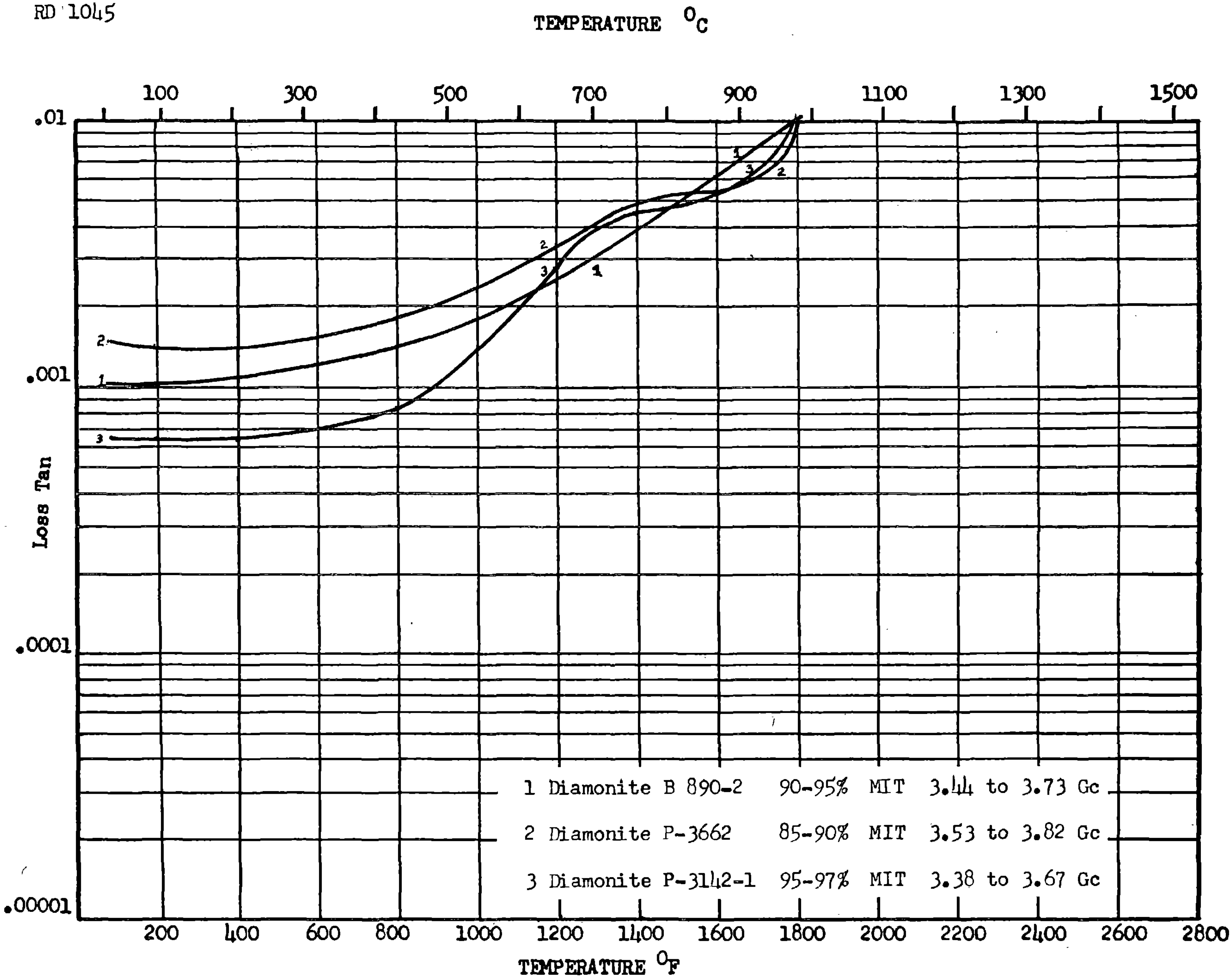

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.01
.001
.0001
.00001
Loss Tan
1 Diamonite B 890-2 90-95% MIT 3.44 to 3.73 Gc
2 Diamonite P-3662 85-90% MIT 3.53 to 3.82 Gc
3 Diamonite P-3142-1 95-97% MIT 3.38 to 3.67 Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 53

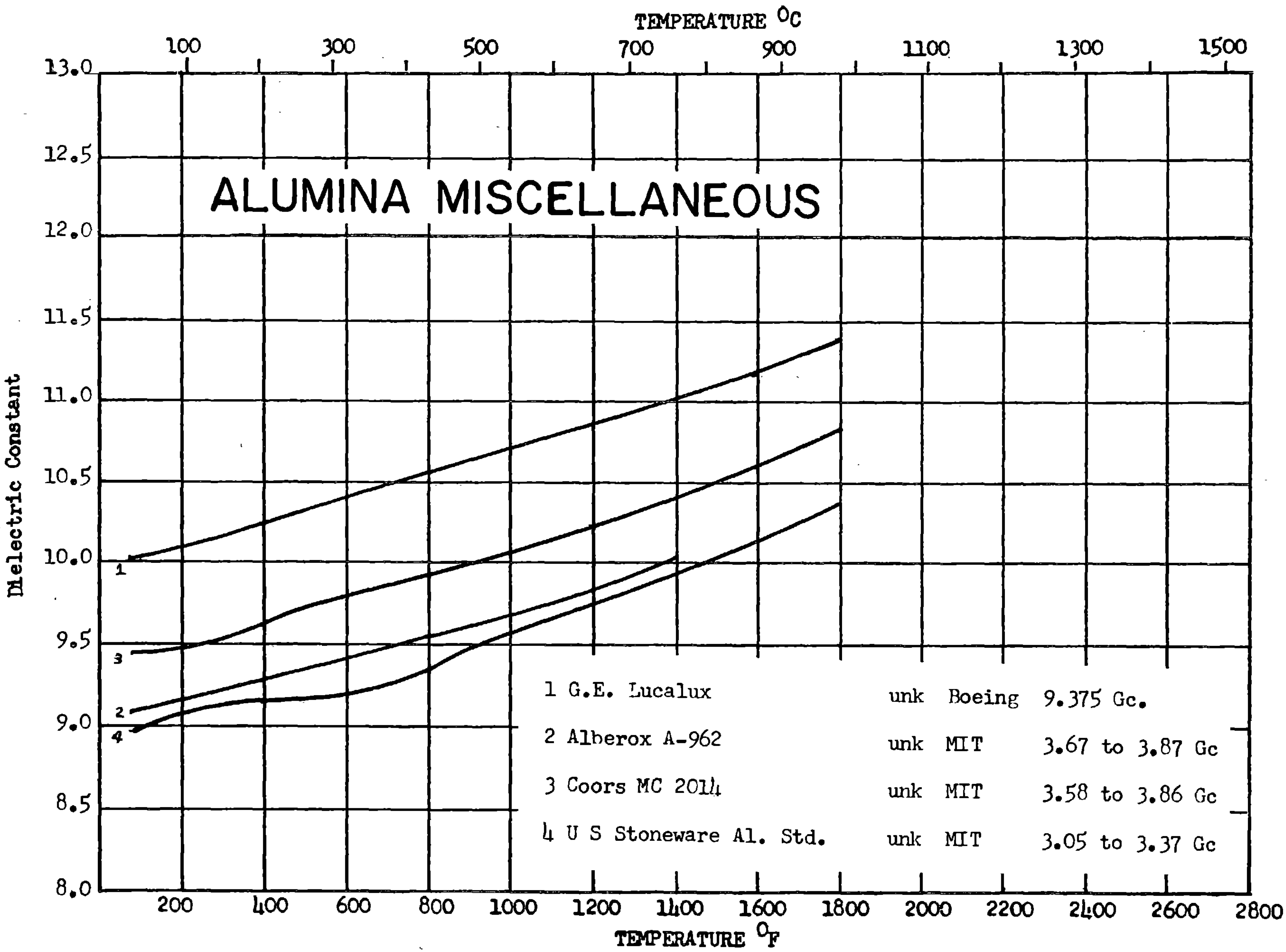

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
13.0
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
Dielectric Constant
ALUMINA MISCELLANEOUS
1
2
3
4
1 G.E. Lucalux unk Boeing 9.375 Gc.
2 Alberox A-962 unk MIT 3.67 to 3.87 Gc
3 Coors MC 2014 unk MIT 3.58 to 3.86 Gc
4 U S Stoneware Al. Std. unk MIT 3.05 to 3.37 Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 54

RD 1046

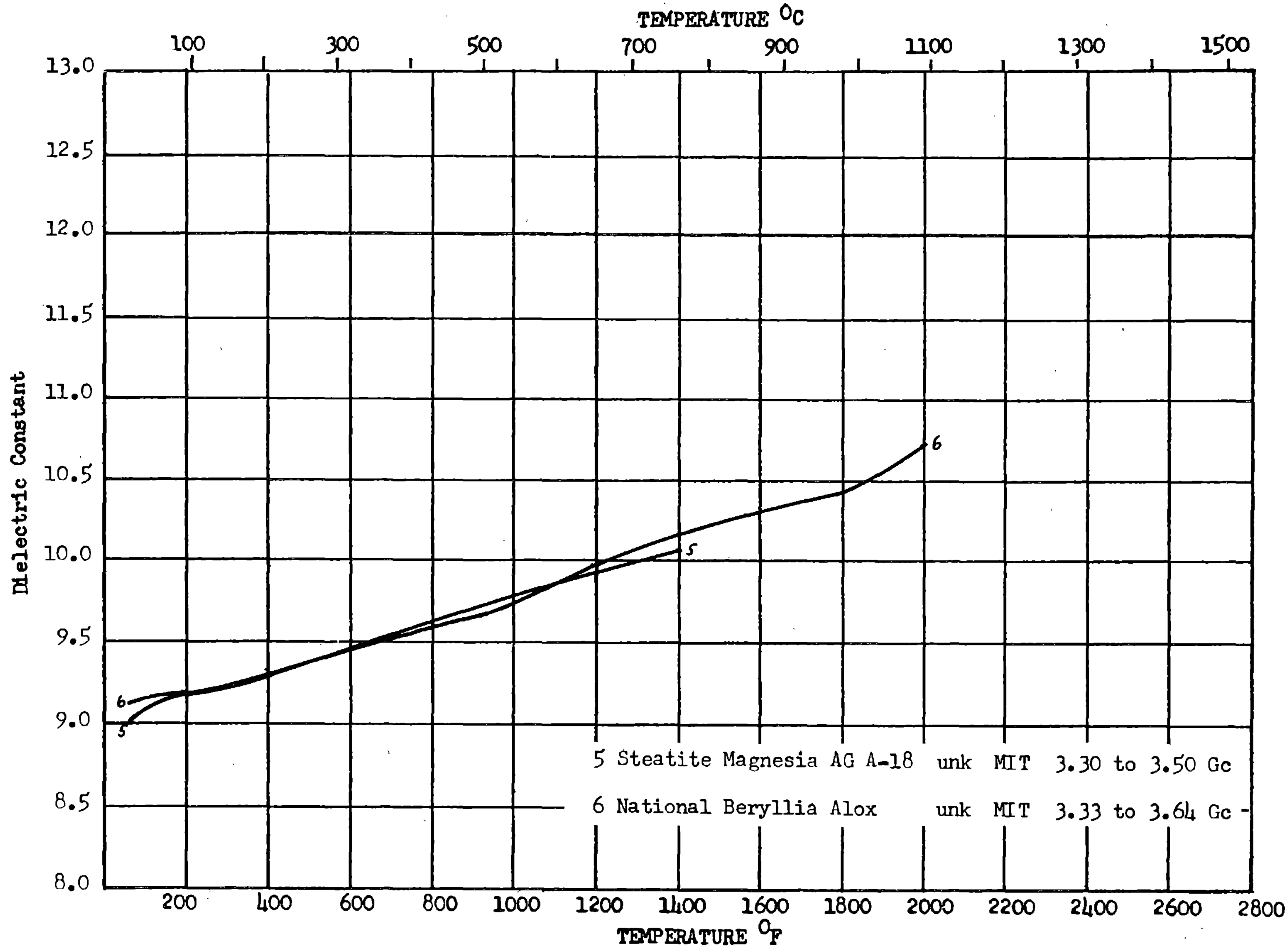


Figure 55

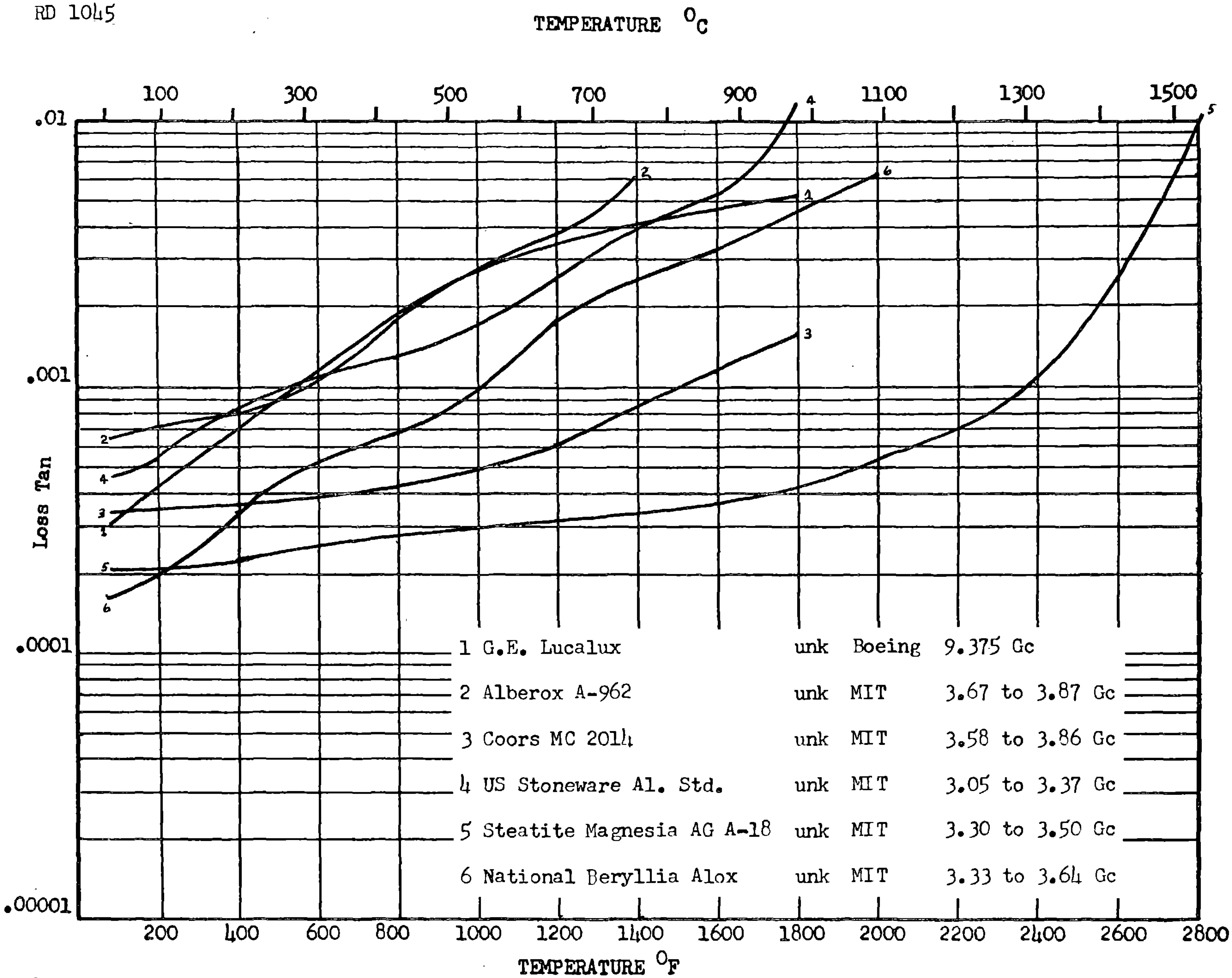

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.01
.001
.0001
.00001
Loss Tan
1 G.E. Lucalux unk Boeing 9.375 Gc
2 Alberox A-962 unk MIT 3.67 to 3.87 Gc
3 Coors MC 2014 unk MIT 3.58 to 3.86 Gc
4 US Stoneware Al. Std. unk MIT 3.05 to 3.37 Gc
5 Steatite Magnesia AG A-18 unk MIT 3.30 to 3.50 Gc
6 National Beryllia Alox unk MIT 3.33 to 3.64 Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 56

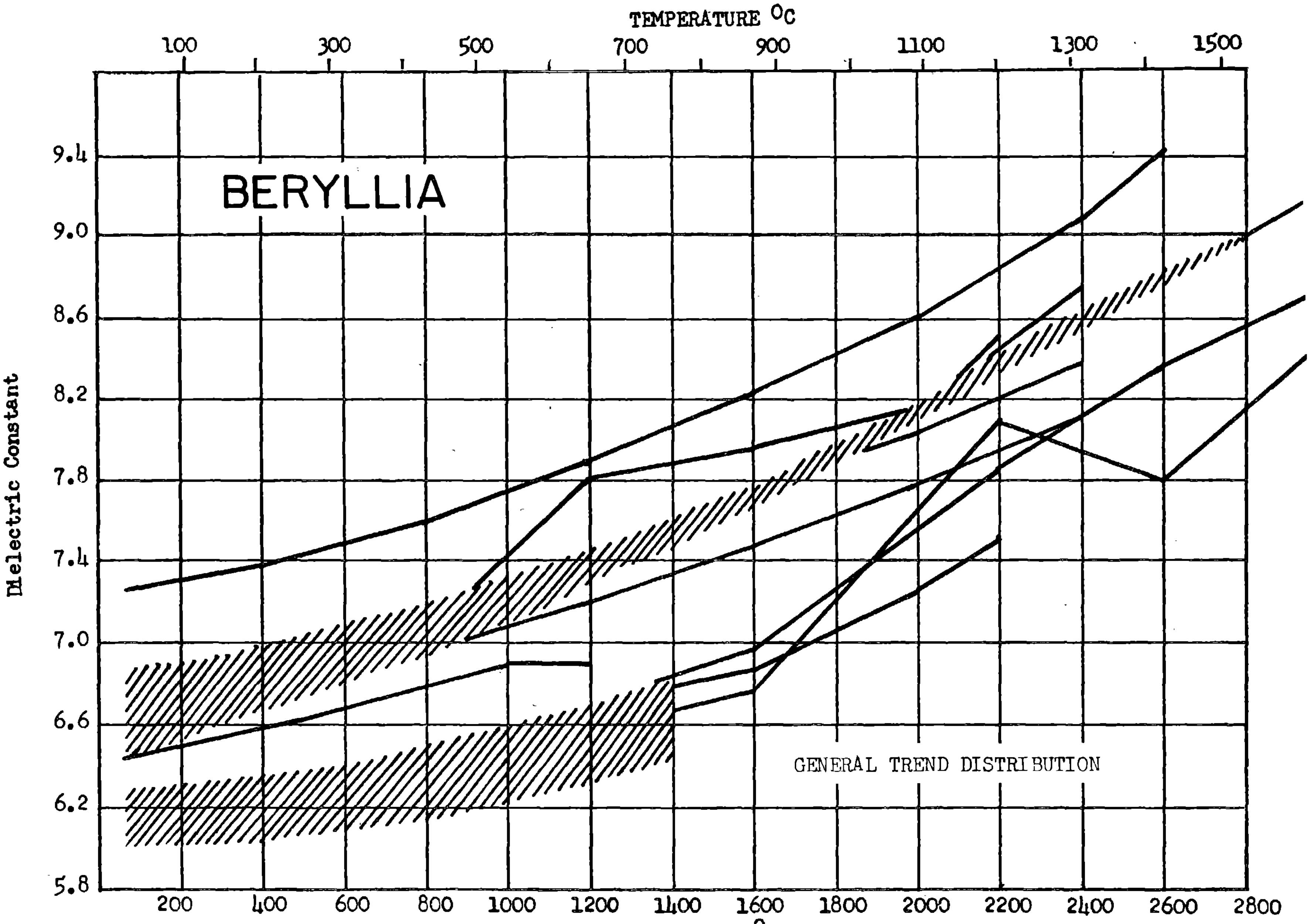

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
BERYLLIA
Dielectric Constant
9.4
9.0
8.6
8.2
7.8
7.4
7.0
6.6
6.2
5.8
GENERAL TREND DISTRIBUTION
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 57

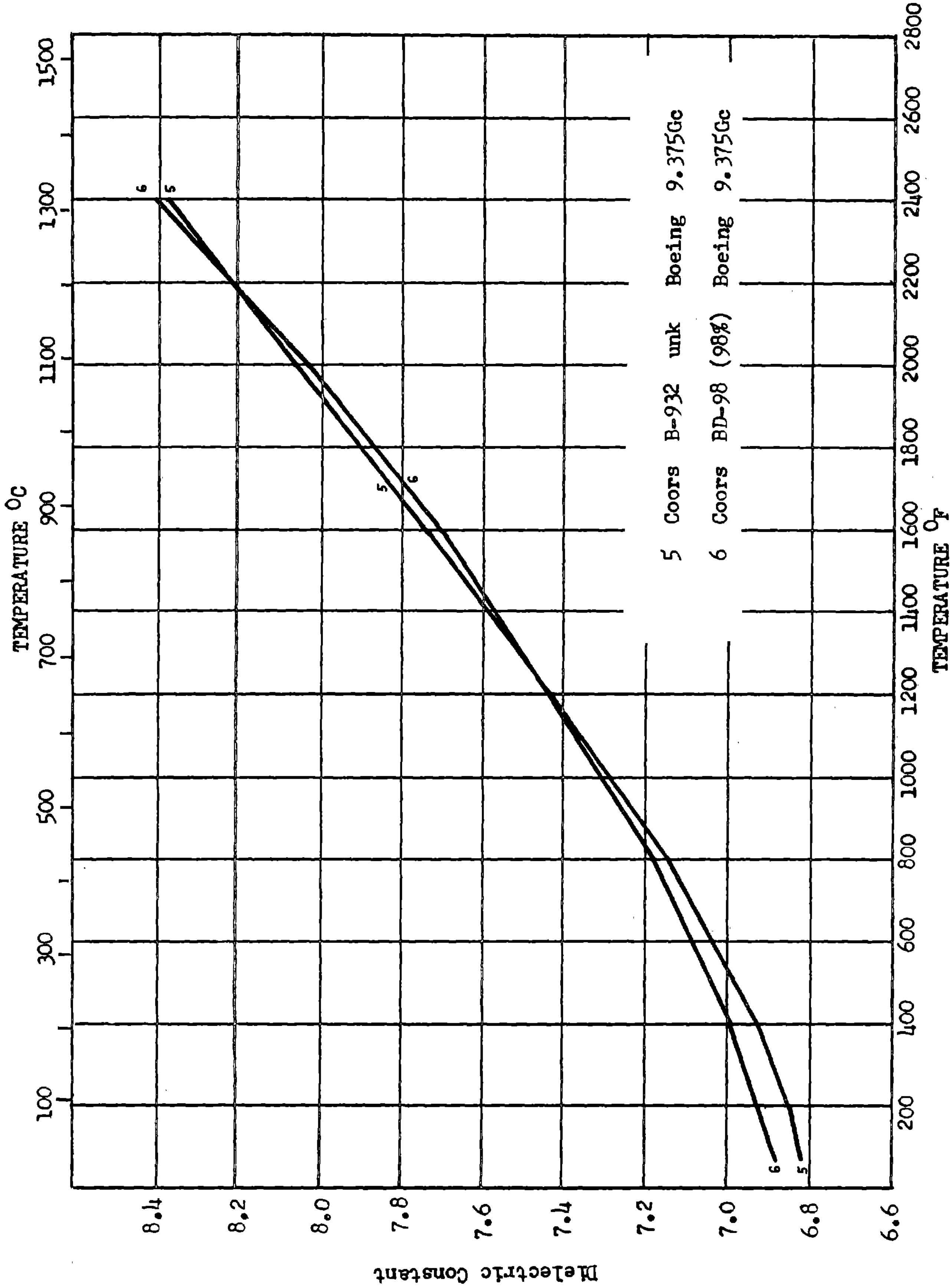

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
TEMPERATURE °F
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
Dielectric Constant
8.4
8.2
8.0
7.8
7.6
7.4
7.2
7.0
6.8
6.6
5 Coors B-932 unk Boeing 9.375Gc
6 Coors BD-98 (98%) Boeing 9.375Gc
5
6

Figure 58

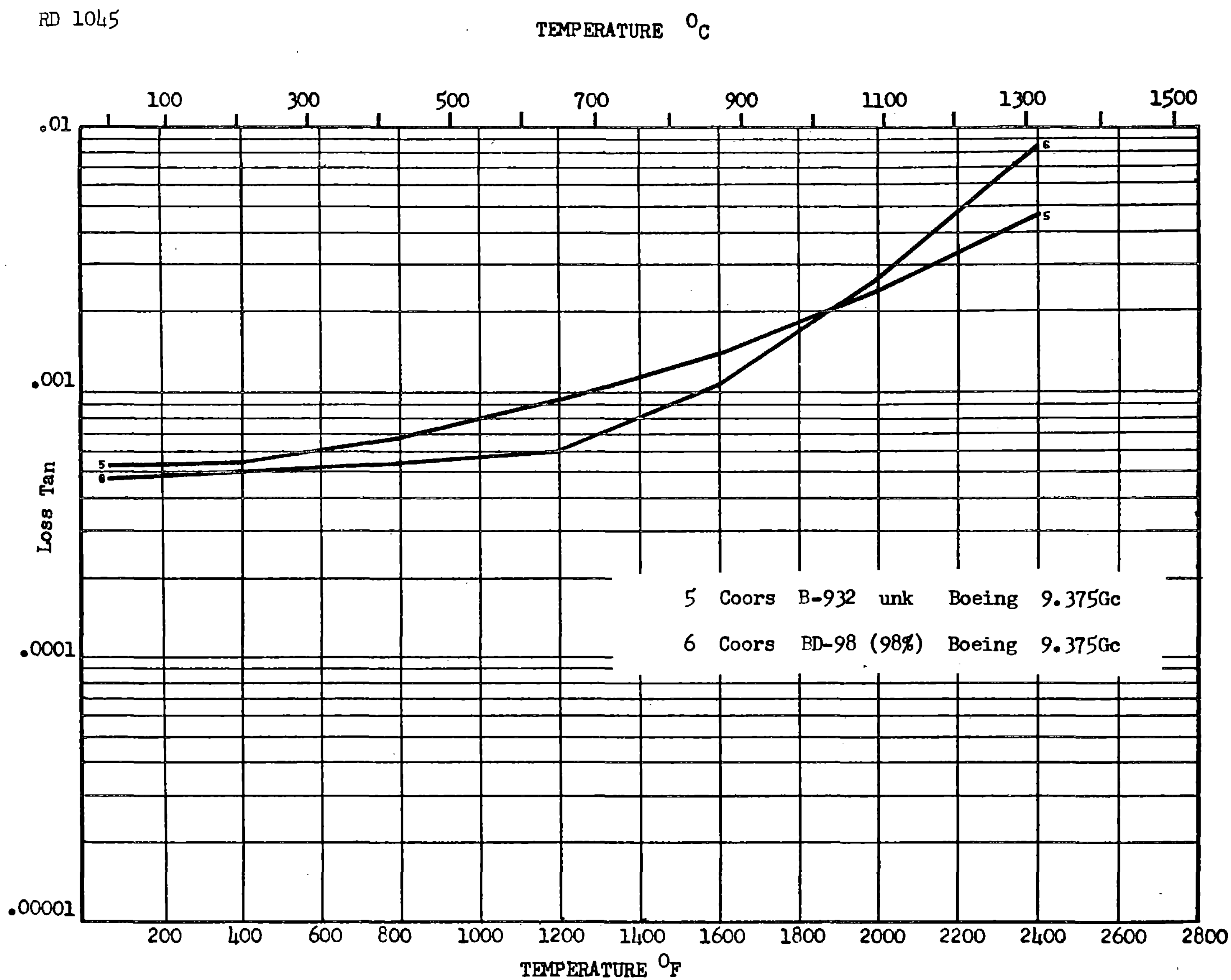

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.01
.001
.0001
.00001
Loss Tan
5
6
5 Coors B-932 unk Boeing 9.375Gc
6 Coors BD-98 (98%) Boeing 9.375Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 59

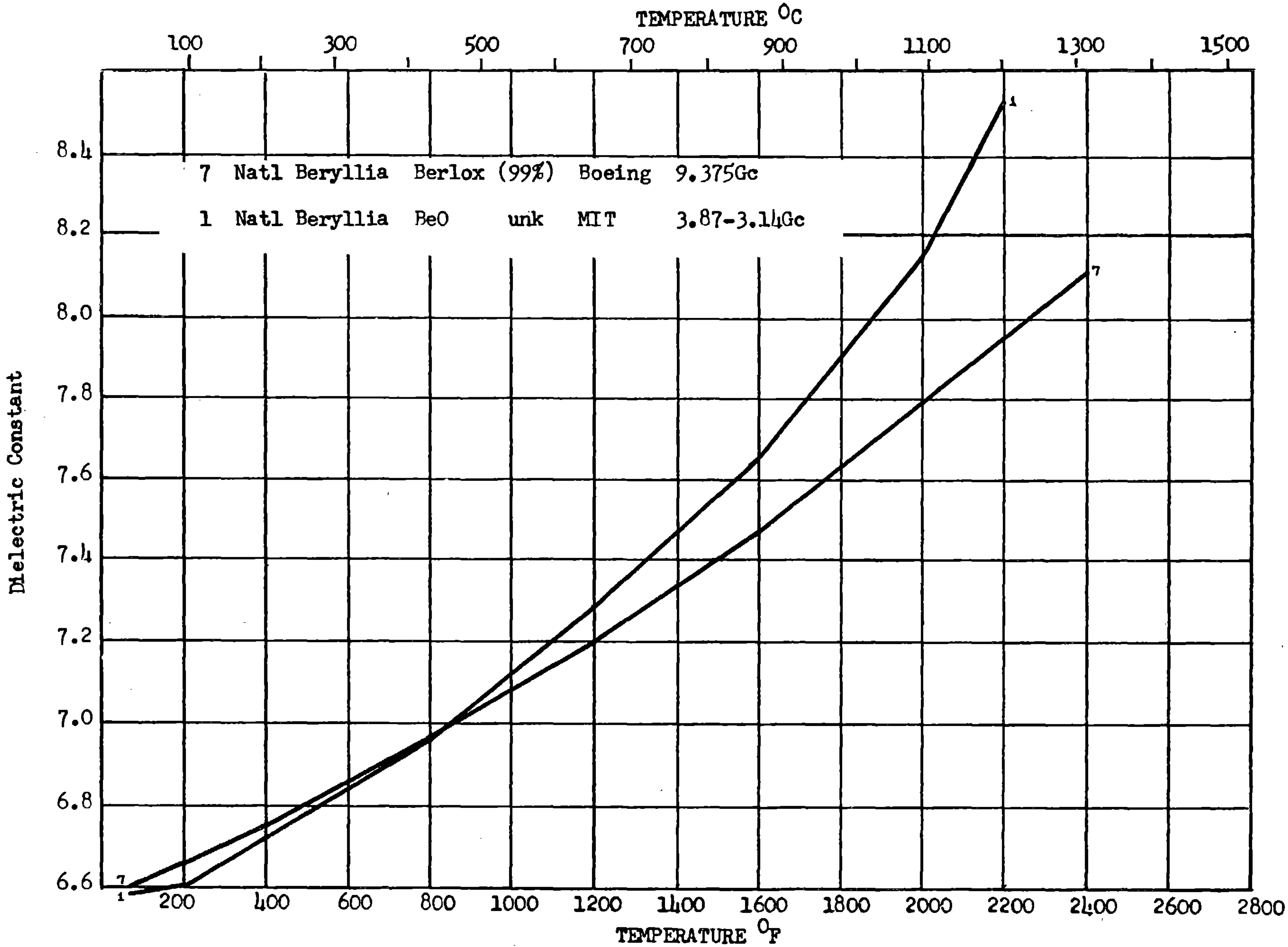

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
7 Natl Beryllia Berlox (99%) Boeing 9.375Gc
1 Natl Beryllia BeO unk MIT 3.87-3.14Gc
Dielectric Constant
8.4
8.2
8.0
7.8
7.6
7.4
7.2
7.0
6.8
6.6
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 60

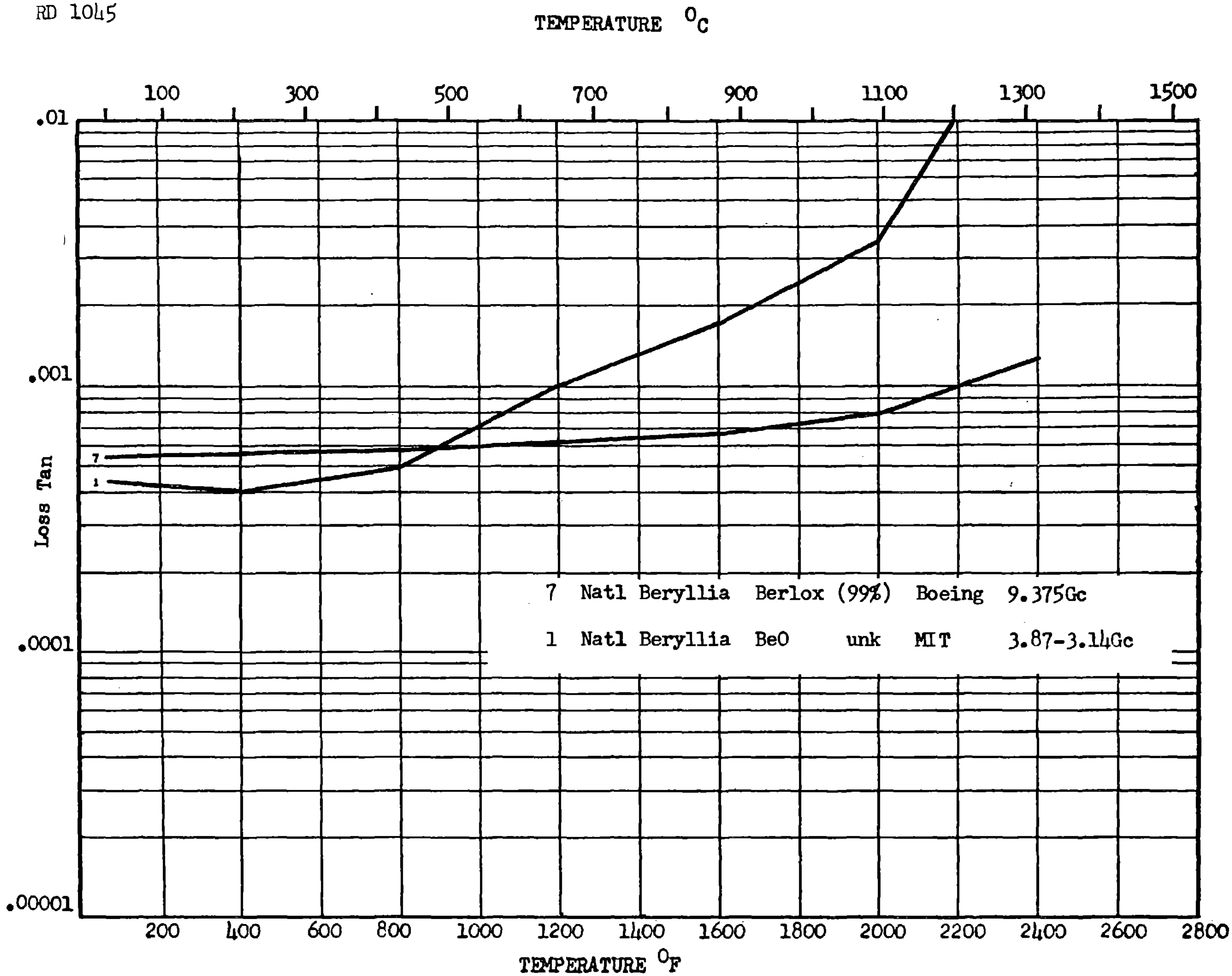

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.01
.001
.0001
.00001
Loss Tan
7
1
7 Natl Beryllia Berlox (99%) Boeing 9.375Gc
1 Natl Beryllia BeO unk MIT 3.87-3.14Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 61

RD 1046

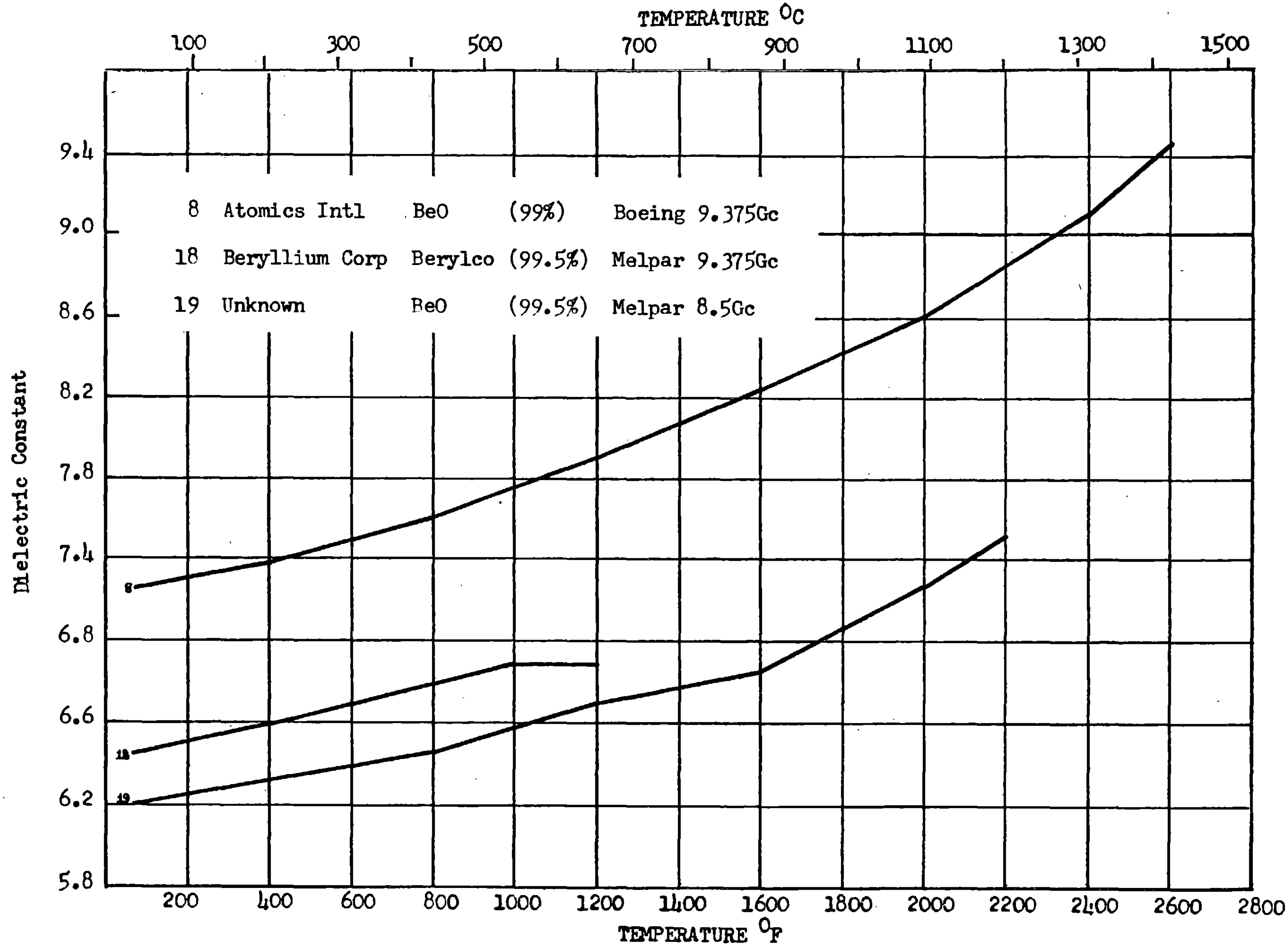


Figure 62

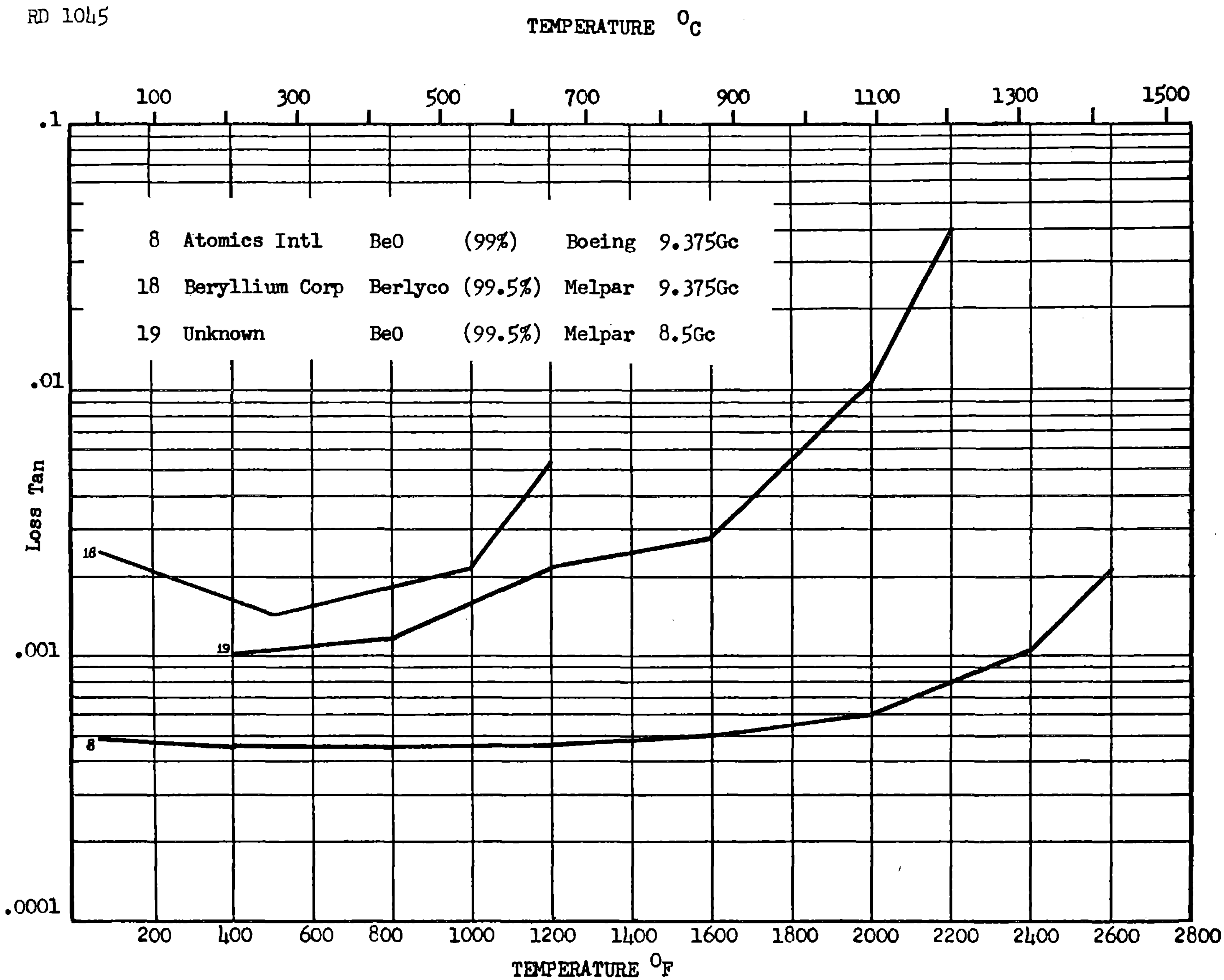

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.1
.01
.001
.0001
Loss Tan
8 Atomics Intl BeO (99%) Boeing 9.375Gc
18 Beryllium Corp Berlyco (99.5%) Melpar 9.375Gc
19 Unknown BeO (99.5%) Melpar 8.5Gc
18
19
8
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 63

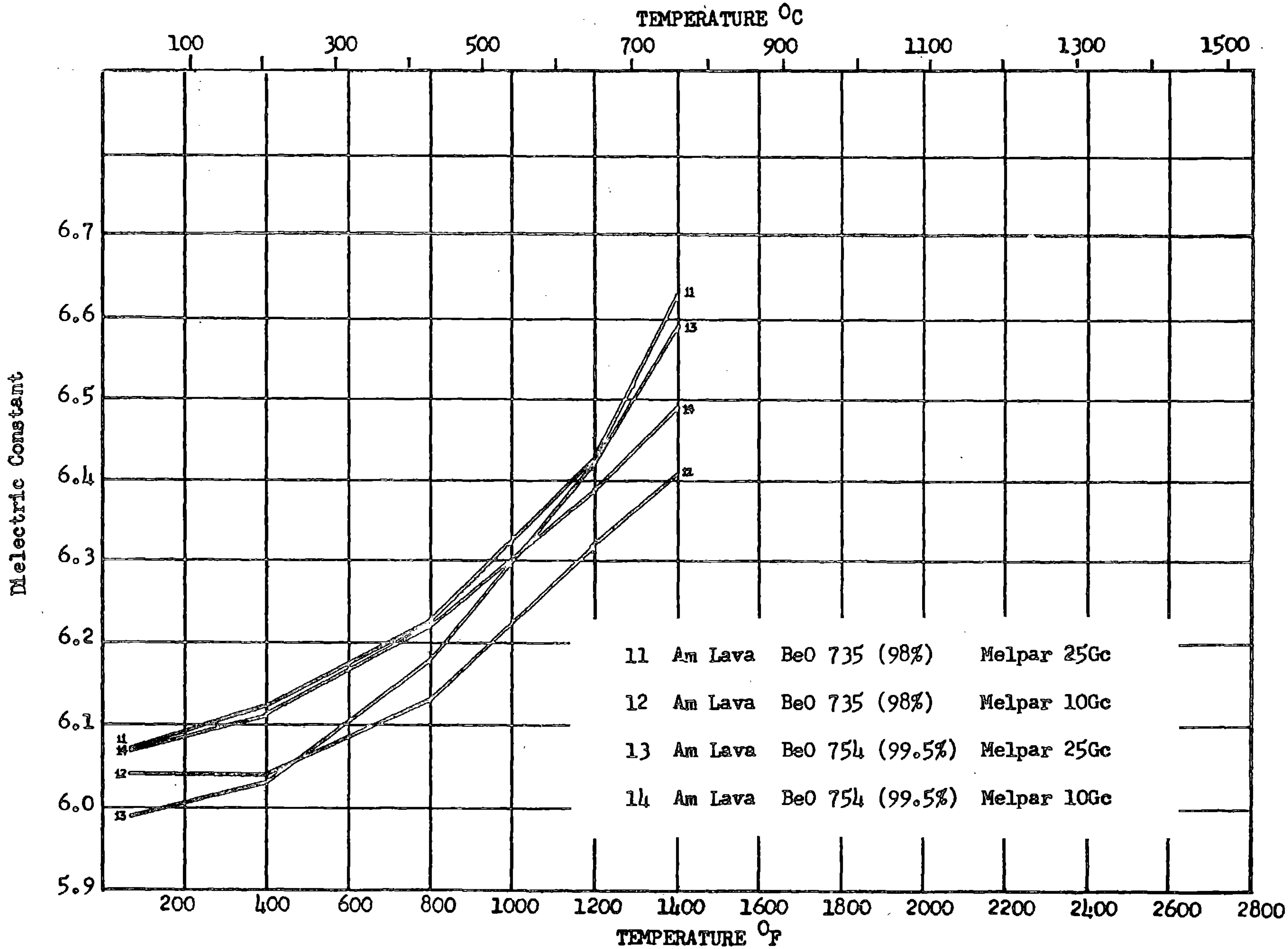

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
Dielectric Constant
6.7
6.6
6.5
6.4
6.3
6.2
6.1
6.0
5.9
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F
11
12
13
14
11 Am Lava BeO 735 (98%) Melpar 25Gc
12 Am Lava BeO 735 (98%) Melpar 10Gc
13 Am Lava BeO 754 (99.5%) Melpar 25Gc
14 Am Lava BeO 754 (99.5%) Melpar 10Gc

Figure 64

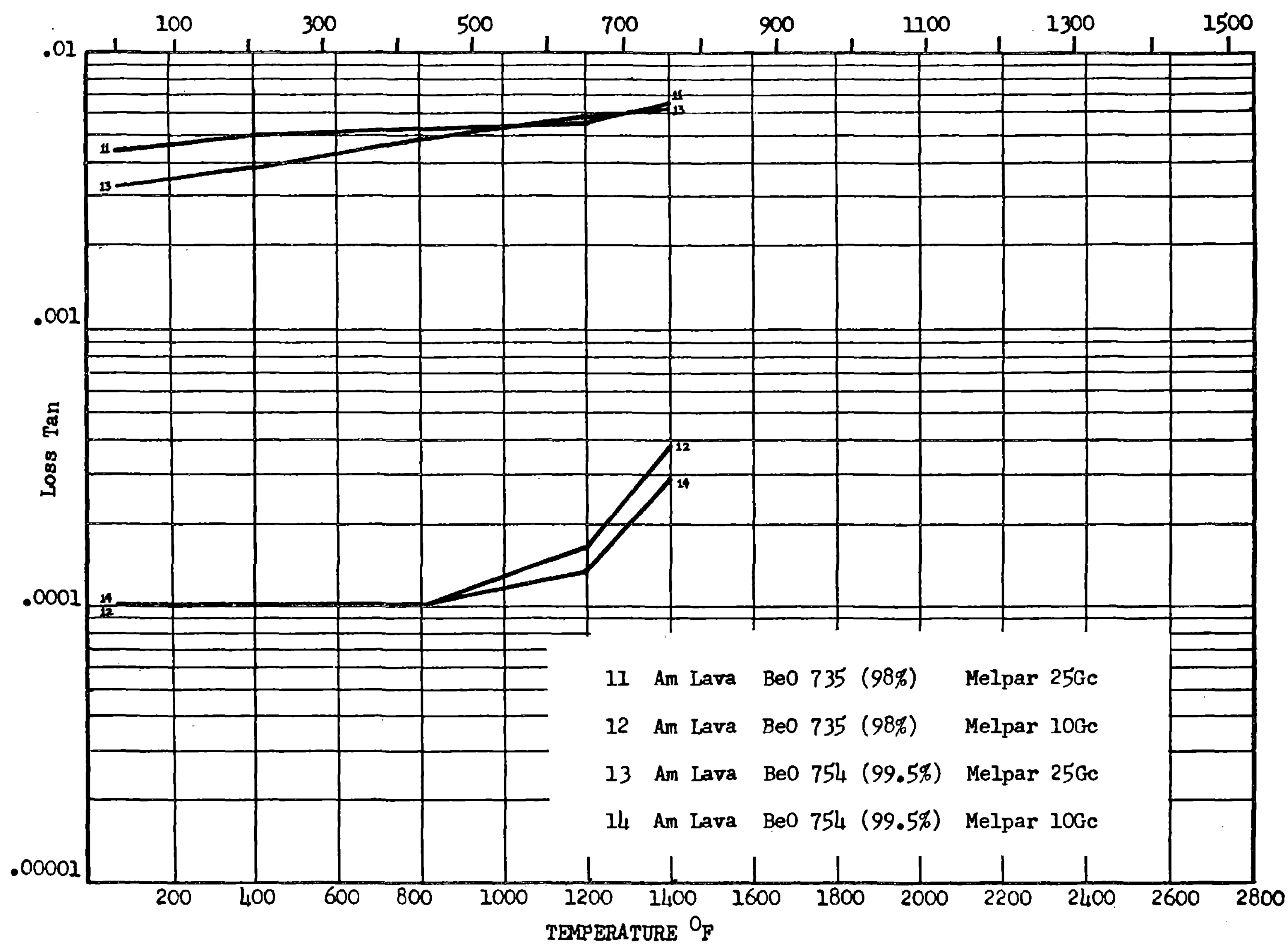

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.01
.001
.0001
.00001
Loss Tan
11
12
13
14
11 Am Lava BeO 735 (98%) Melpar 25Gc
12 Am Lava BeO 735 (98%) Melpar 10Gc
13 Am Lava BeO 754 (99.5%) Melpar 25Gc
14 Am Lava BeO 754 (99.5%) Melpar 10Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 65

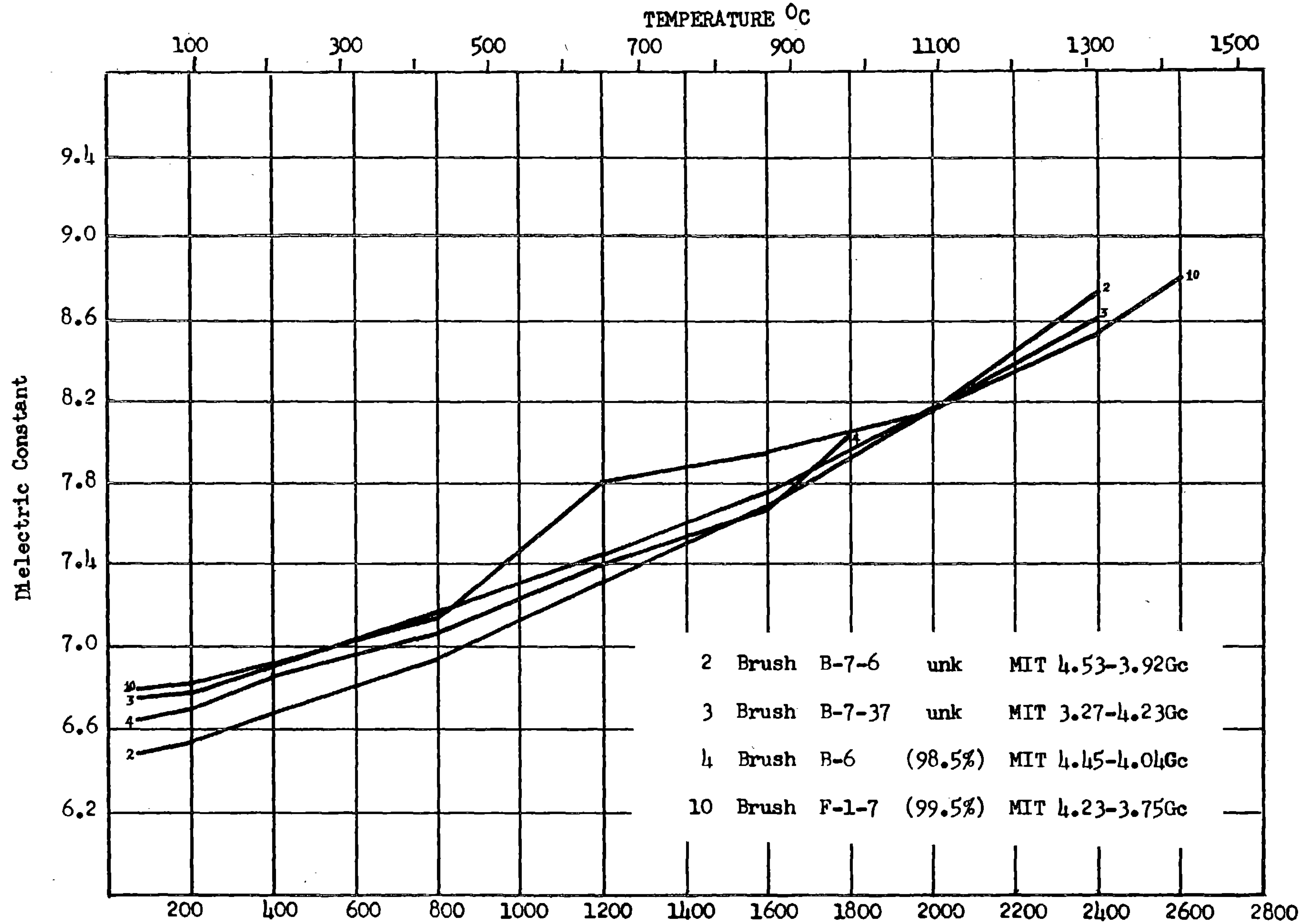

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
Dielectric Constant
9.4
9.0
8.6
8.2
7.8
7.4
7.0
6.6
6.2
2 Brush B-7-6 unk MIT 4.53-3.92Gc
3 Brush B-7-37 unk MIT 3.27-4.23Gc
4 Brush B-6 (98.5%) MIT 4.45-4.04Gc
10 Brush F-1-7 (99.5%) MIT 4.23-3.75Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 66

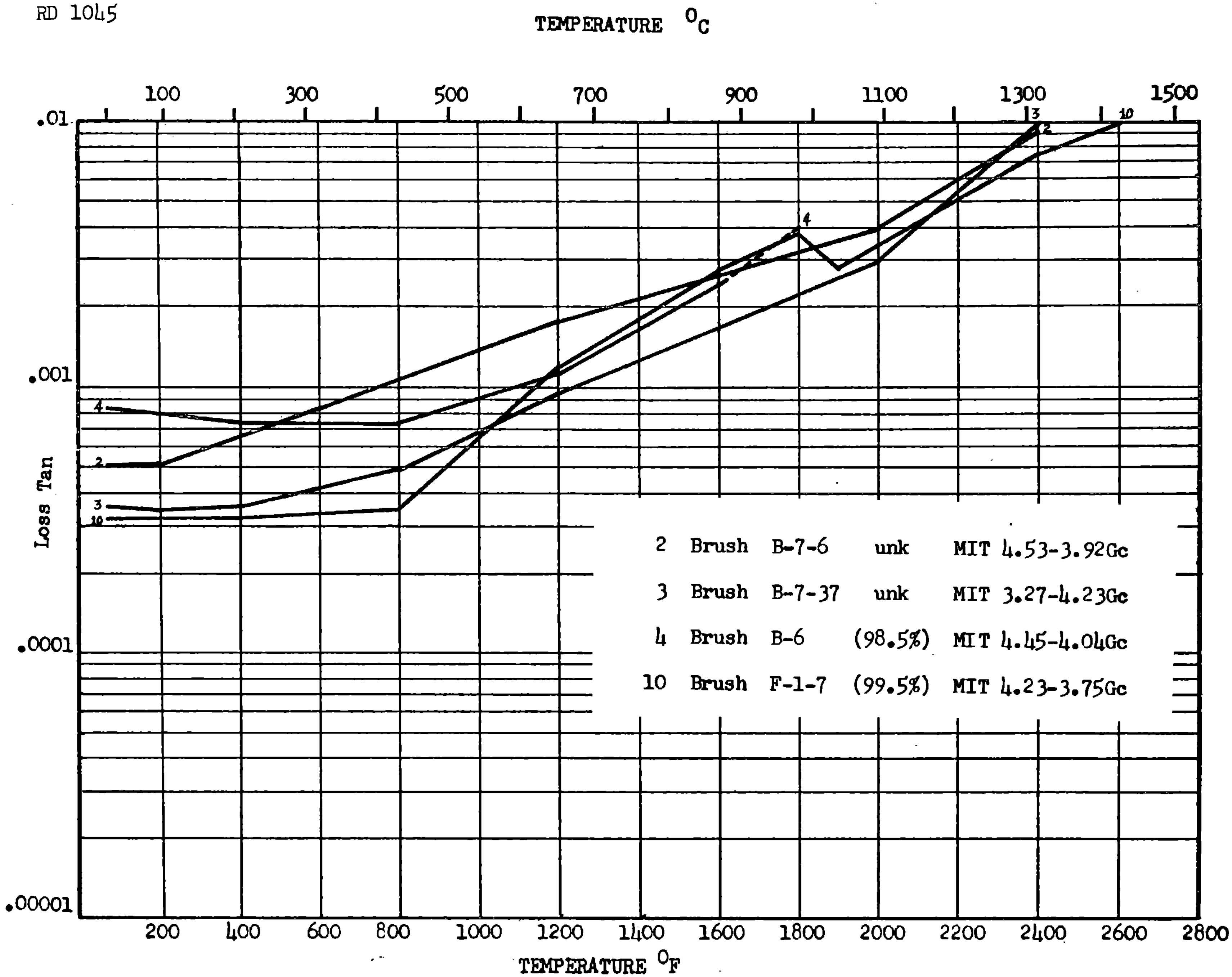

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.01
.001
.0001
.00001
Loss Tan
4
2
3
10
2 Brush B-7-6 unk MIT 4.53-3.92Gc
3 Brush B-7-37 unk MIT 3.27-4.23Gc
4 Brush B-6 (98.5%) MIT 4.45-4.04Gc
10 Brush F-1-7 (99.5%) MIT 4.23-3.75Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 67

RD 1046

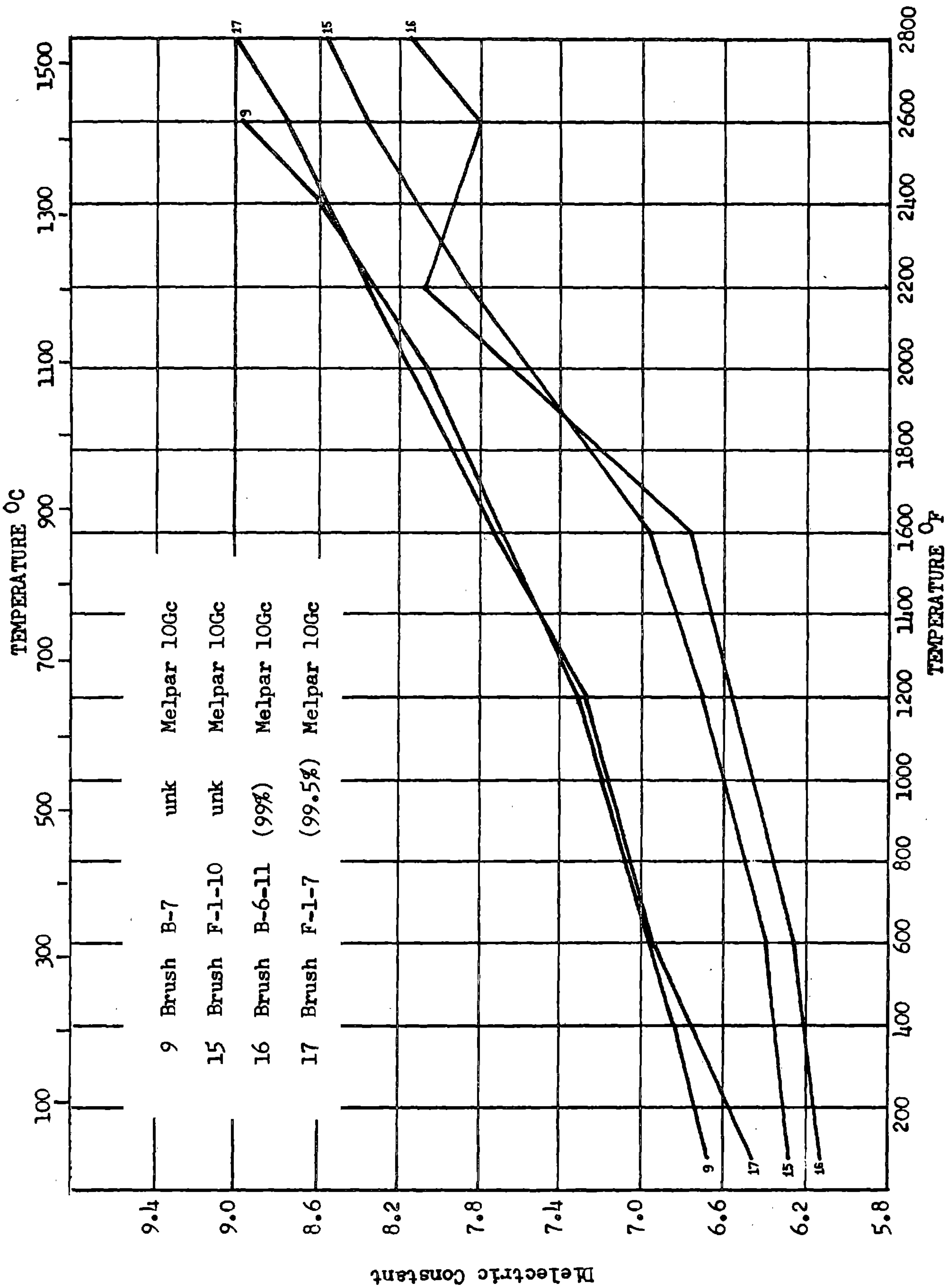


Figure 68

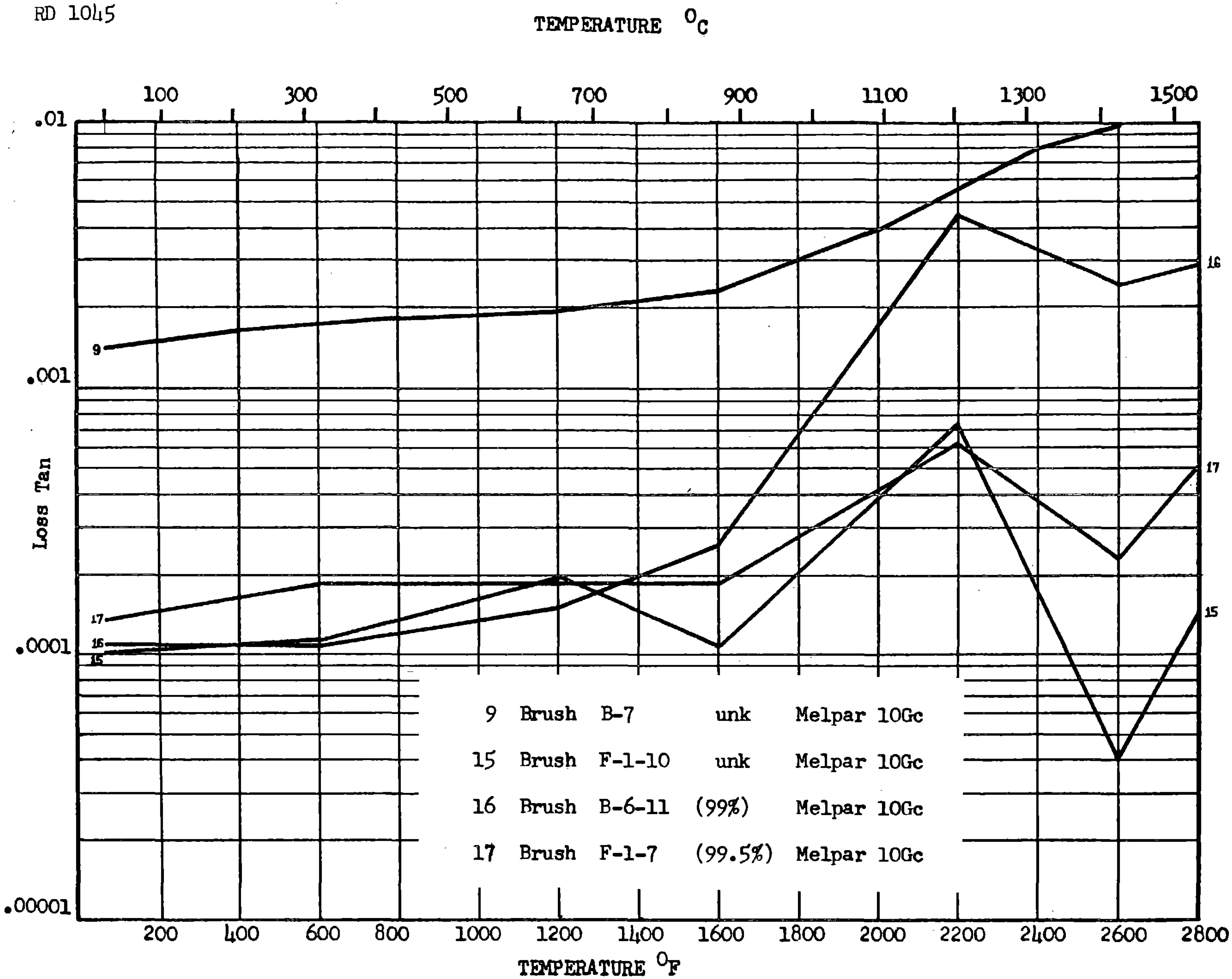

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.01
.001
.0001
.00001
Loss Tan
9
15
16
17
9 Brush B-7 unk Melpar 10Gc
15 Brush F-1-10 unk Melpar 10Gc
16 Brush B-6-11 (99%) Melpar 10Gc
17 Brush F-1-7 (99.5%) Melpar 10Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 69

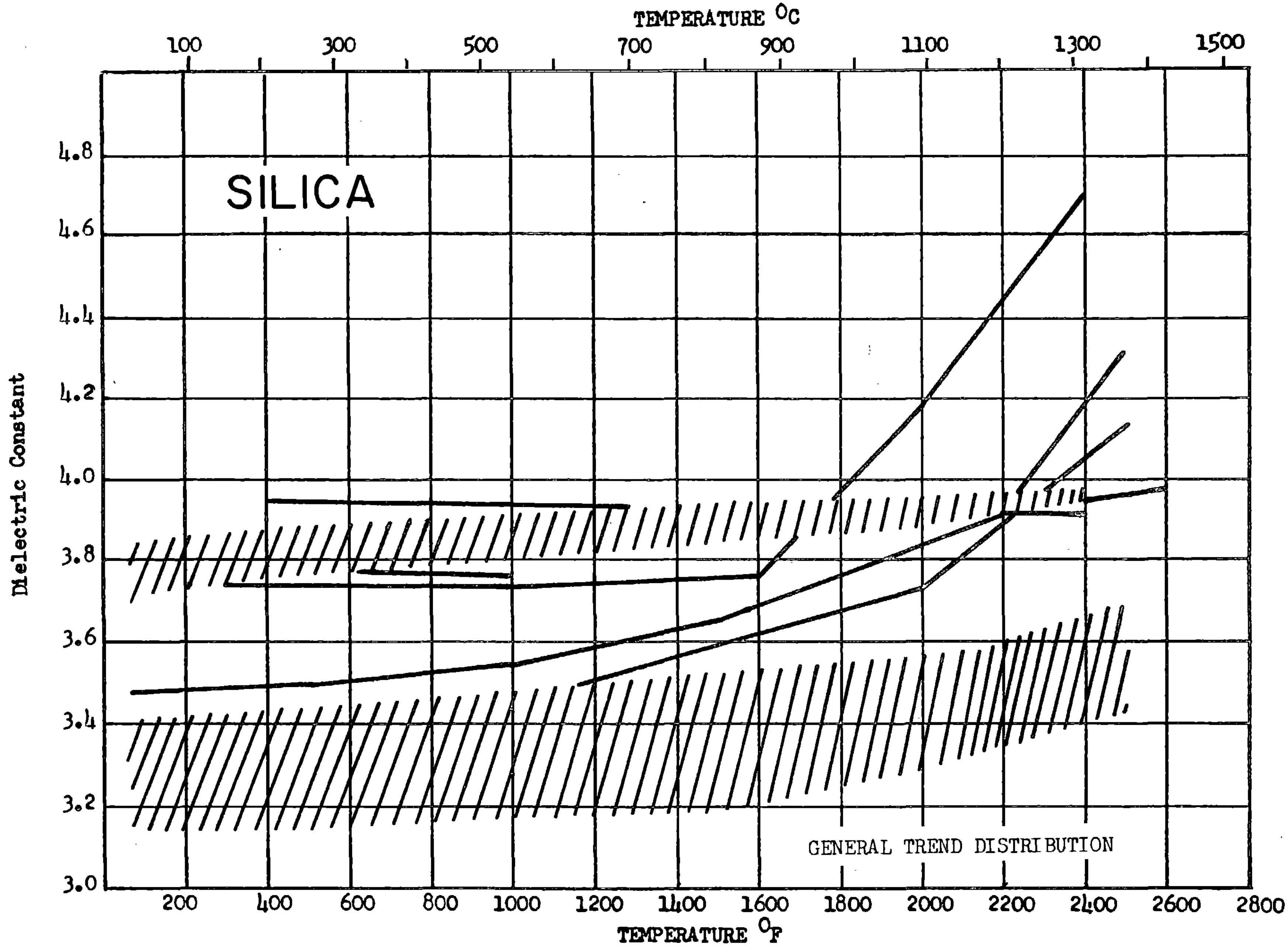

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
Dielectric Constant
SILICA
GENERAL TREND DISTRIBUTION
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 70

RD 1046

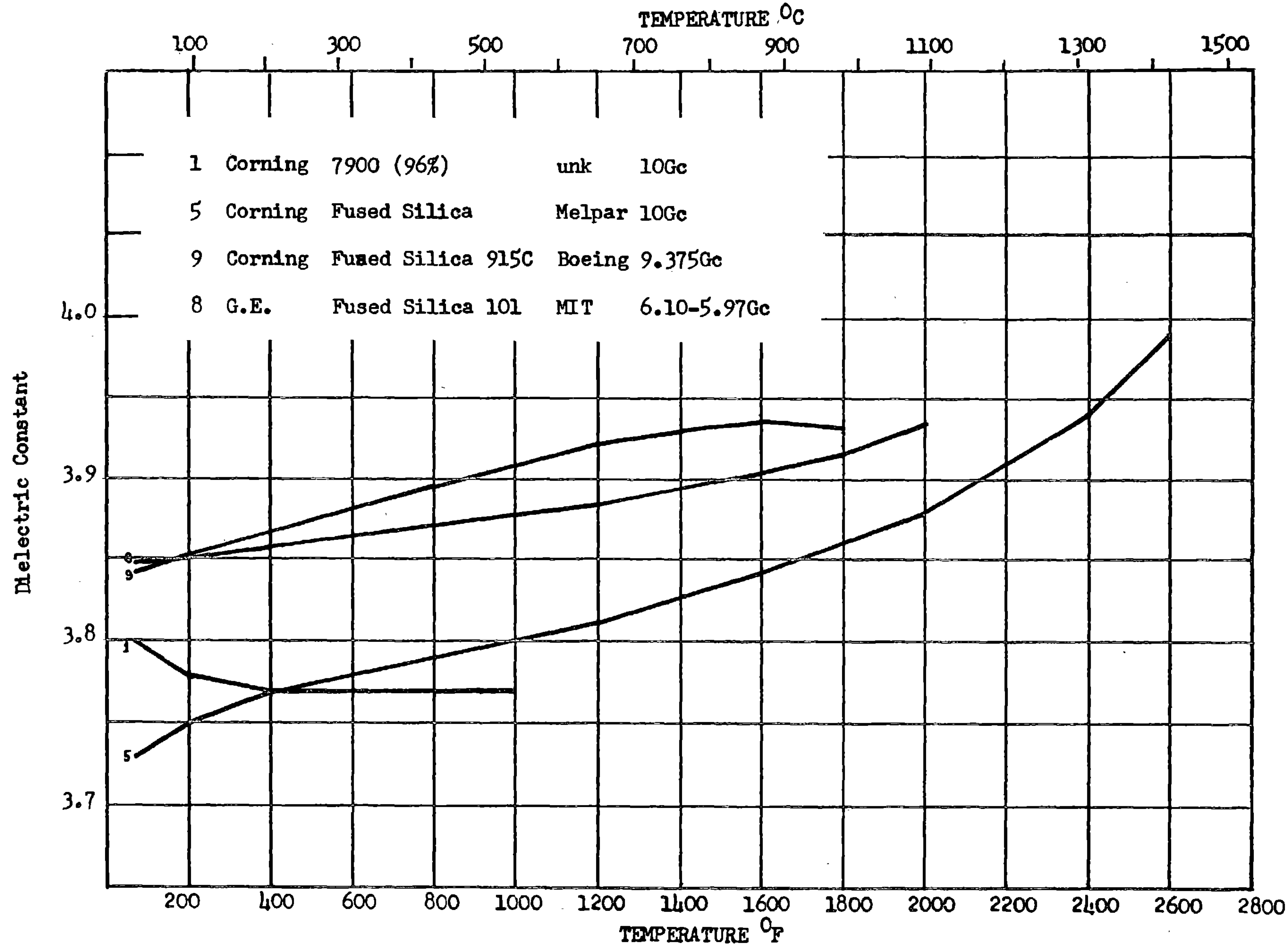


Figure 71

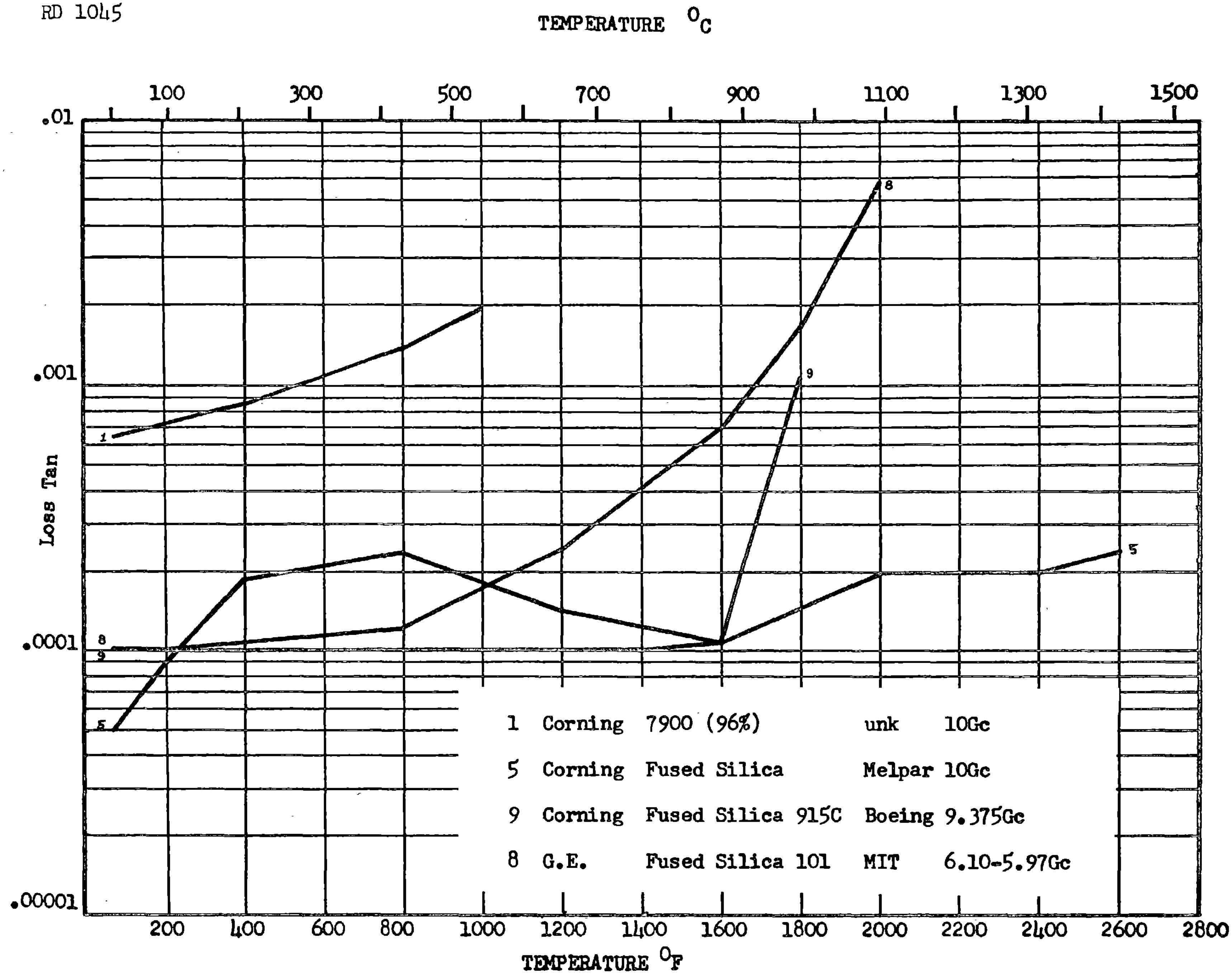

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.01
.001
.0001
.00001
Loss Tan
1
5
8
9
1 Corning 7900 (96%) unk 10Gc
5 Corning Fused Silica Melpar 10Gc
9 Corning Fused Silica 915C Boeing 9.375Gc
8 G.E. Fused Silica 101 MIT 6.10-5.97Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 72

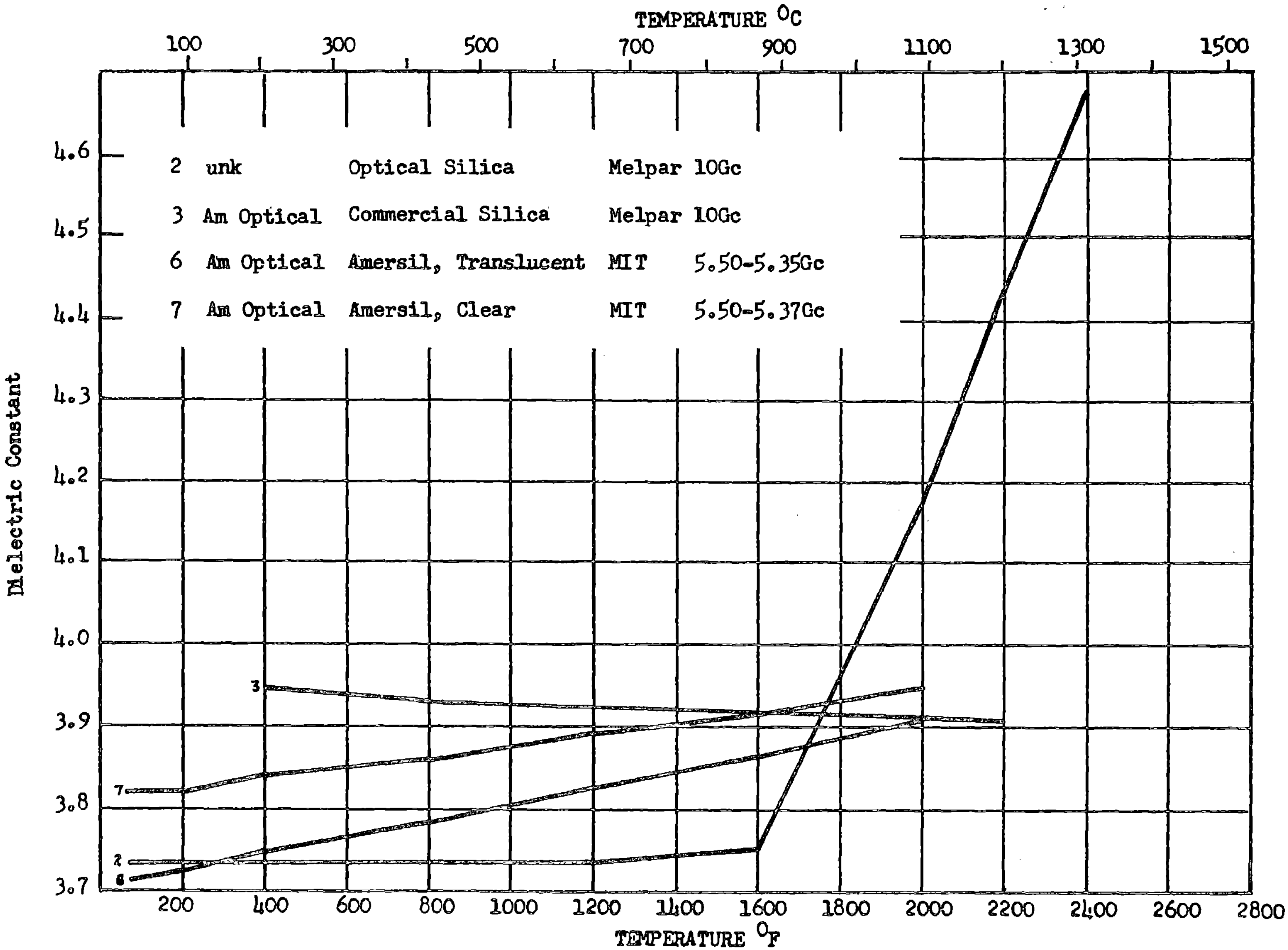

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
2 unk Optical Silica Melpar 10Gc
3 Am Optical Commercial Silica Melpar 10Gc
6 Am Optical Amersil, Translucent MIT 5.50-5.35Gc
7 Am Optical Amersil, Clear MIT 5.50-5.37Gc
Dielectric Constant
4.6
4.5
4.4
4.3
4.2
4.1
4.0
3.9
3.8
3.7
3
7
2
6
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 73

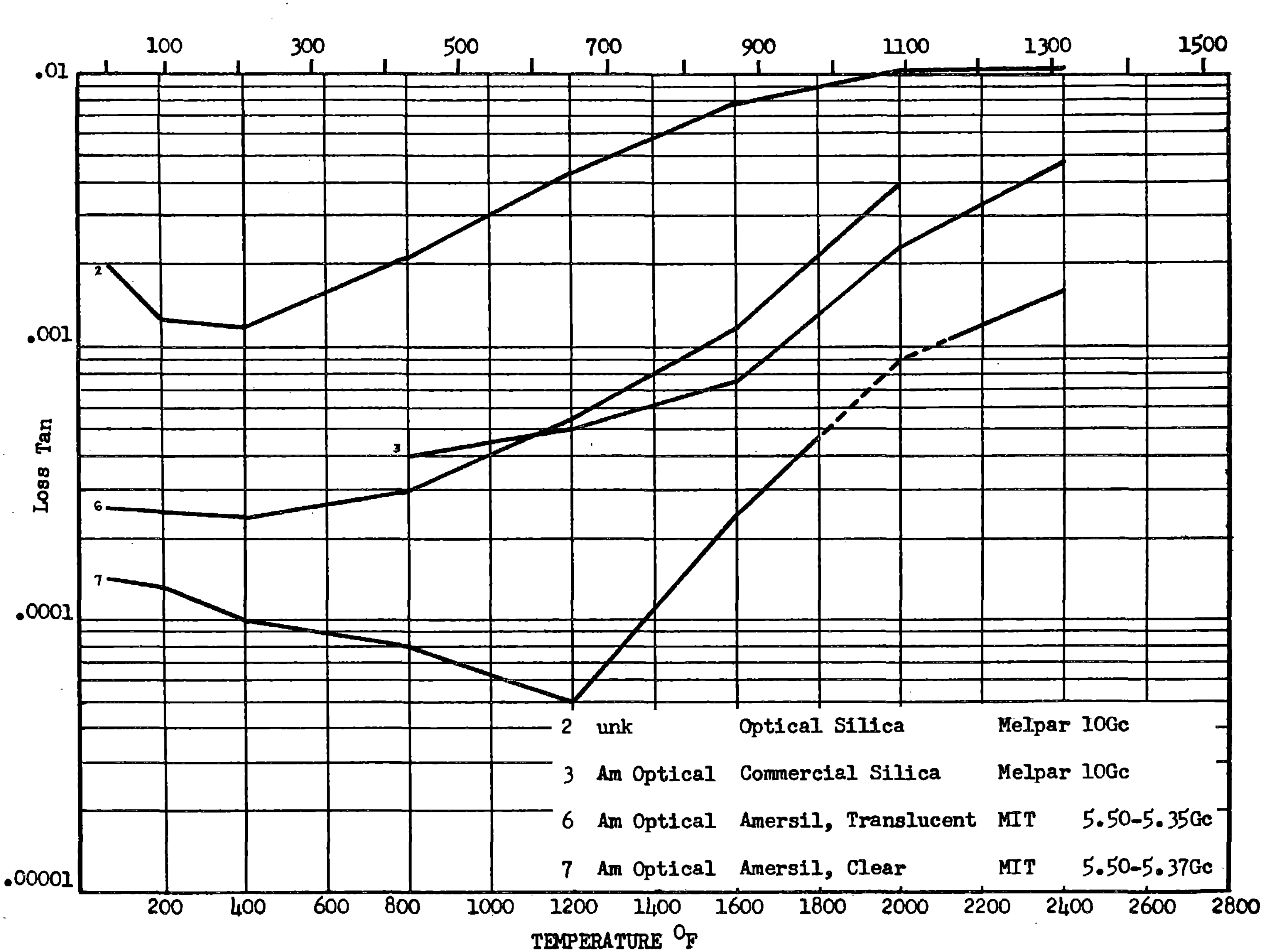

TEMPERATURE $^{\circ}C$
100
300
500
700
900
1100
1300
1500
.01
.001
.0001
.00001
Loss Tan
2
3
6
7
2 unk Optical Silica Melpar 10Gc
3 Am Optical Commercial Silica Melpar 10Gc
6 Am Optical Amersil, Translucent MIT 5.50-5.35Gc
7 Am Optical Amersil, Clear MIT 5.50-5.37Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE $^{\circ}F$

Figure 74

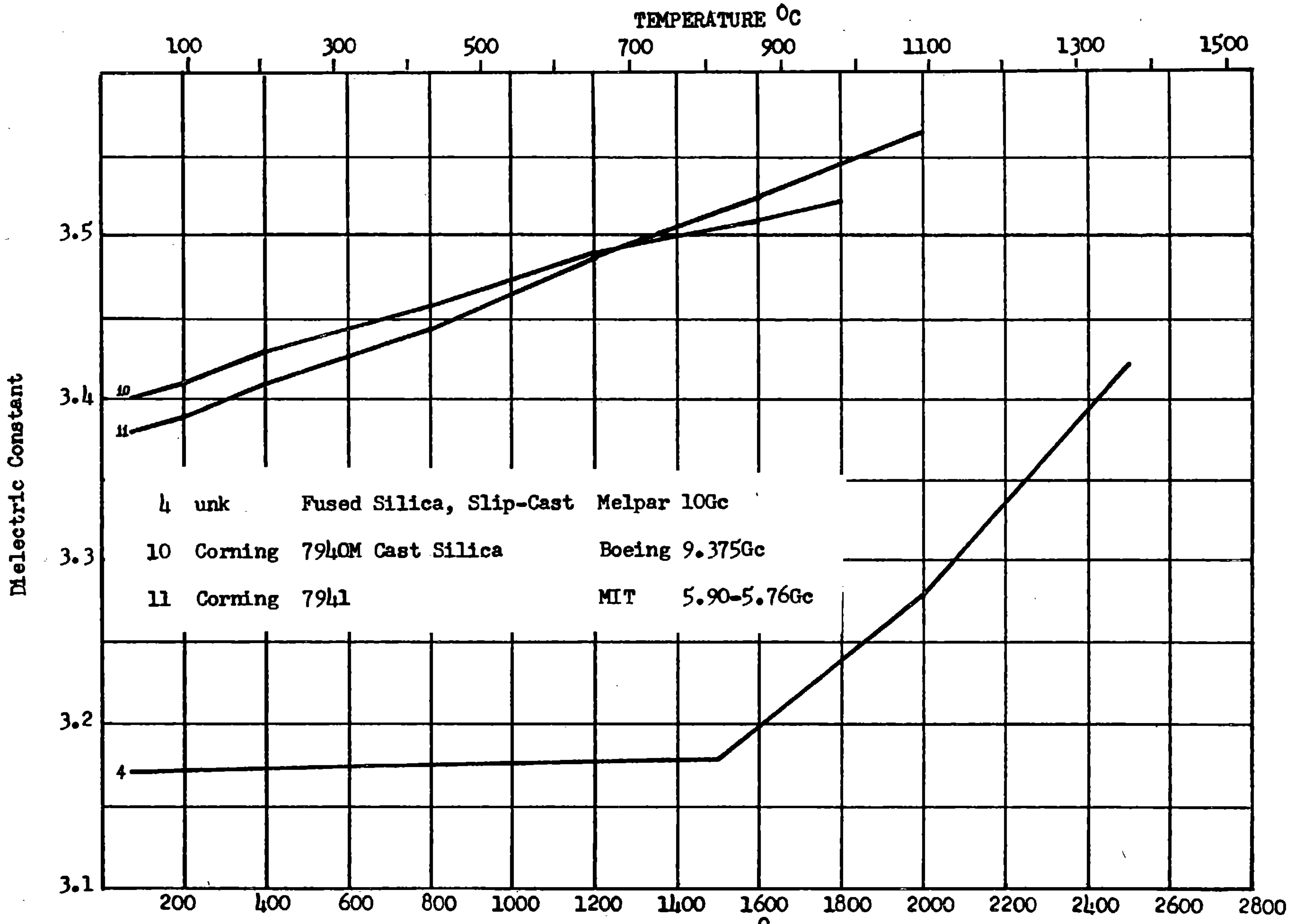

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
Dielectric Constant
3.5
3.4
3.3
3.2
3.1
10
11
4
4 unk Fused Silica, Slip-Cast Melpar 10Gc
10 Corning 7940M Cast Silica Boeing 9.375Gc
11 Corning 7941 MIT 5.90-5.76Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 75

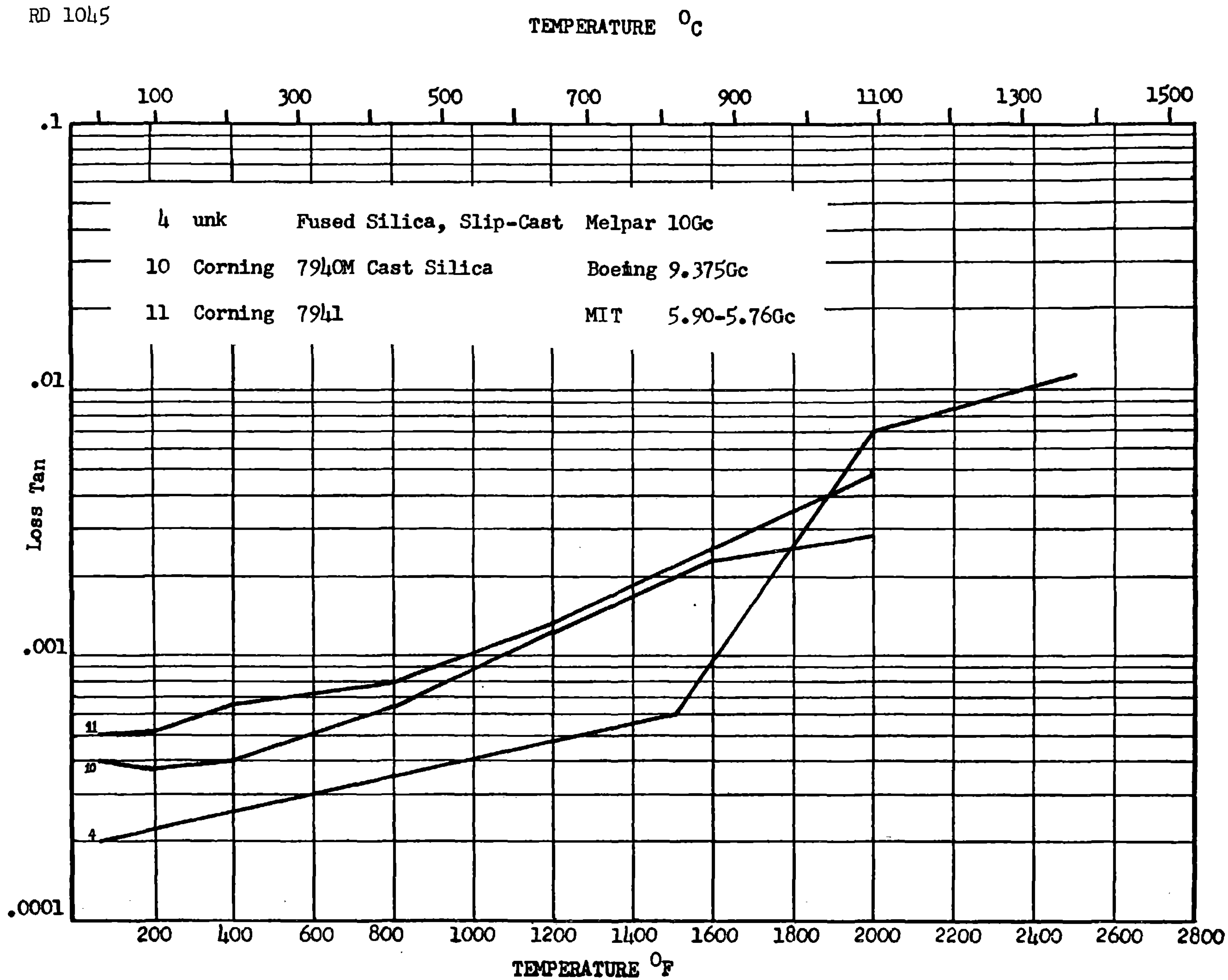

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.1
.01
.001
.0001
Loss Tan
4 unk Fused Silica, Slip-Cast Melpar 10Gc
10 Corning 7940M Cast Silica Boeing 9.375Gc
11 Corning 7941 MIT 5.90-5.76Gc
11
10
4
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 76

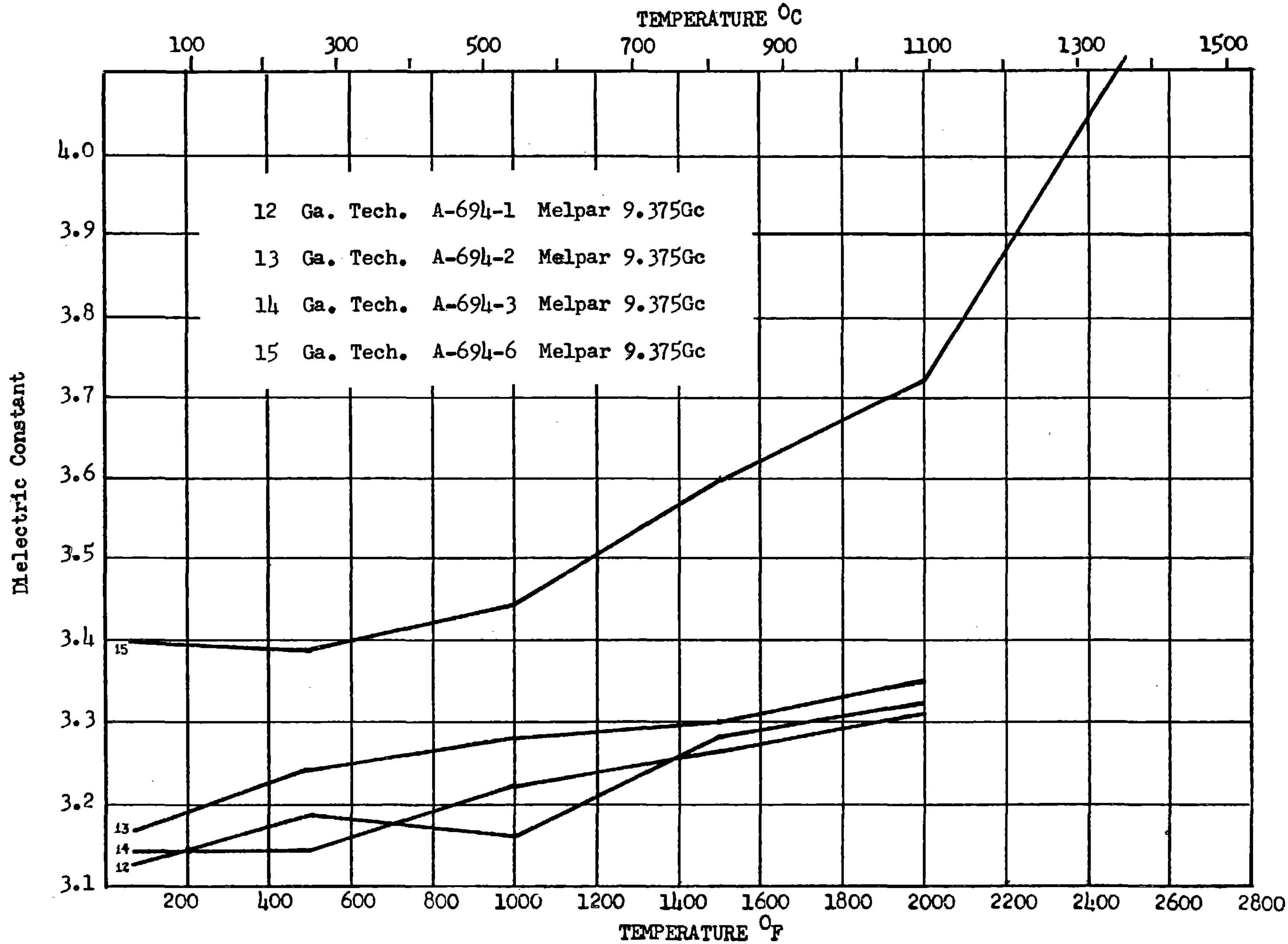

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
Dielectric Constant
4.0
3.9
3.8
3.7
3.6
3.5
3.4
3.3
3.2
3.1
12 Ga. Tech. A-694-1 Melpar 9.375Gc
13 Ga. Tech. A-694-2 Melpar 9.375Gc
14 Ga. Tech. A-694-3 Melpar 9.375Gc
15 Ga. Tech. A-694-6 Melpar 9.375Gc
15
13
14
12
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 77

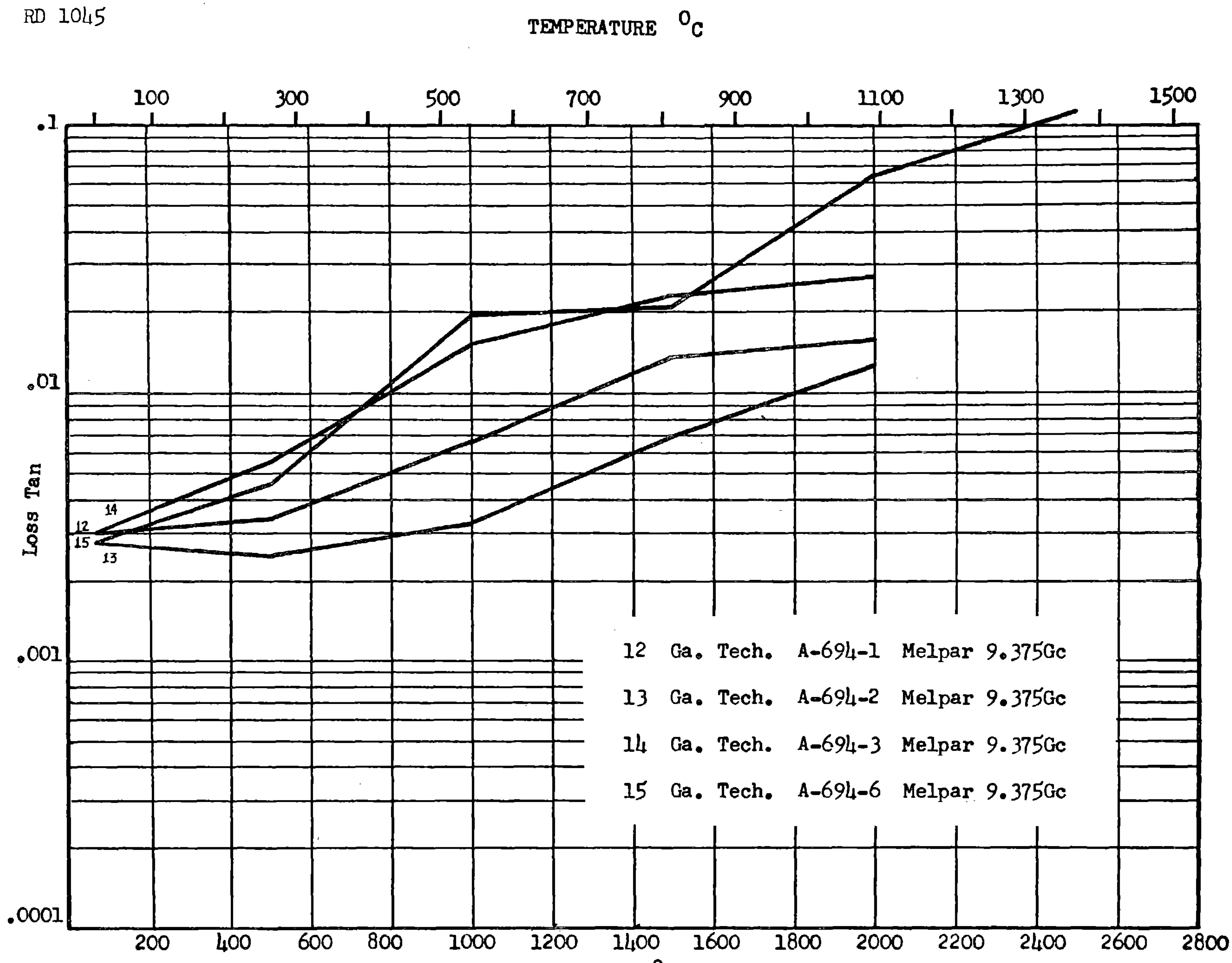

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.1
.01
.001
.0001
Loss Tan
12
13
14
15
12 Ga. Tech. A-694-1 Melpar 9.375Gc
13 Ga. Tech. A-694-2 Melpar 9.375Gc
14 Ga. Tech. A-694-3 Melpar 9.375Gc
15 Ga. Tech. A-694-6 Melpar 9.375Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 78

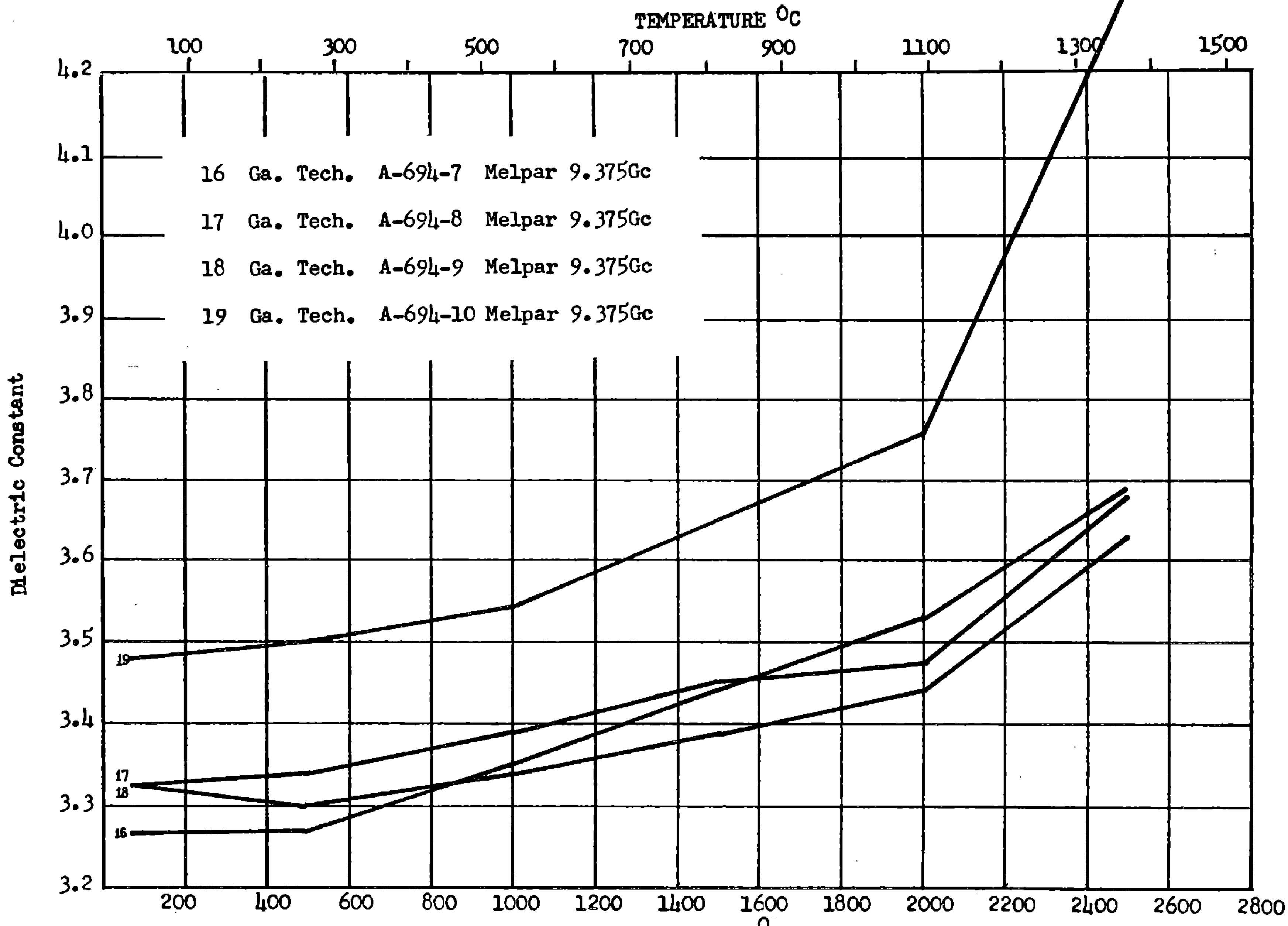

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
4.2
4.1
4.0
3.9
3.8
3.7
3.6
3.5
3.4
3.3
3.2
Dielectric Constant
16 Ga. Tech. A-694-7 Melpar 9.375Gc
17 Ga. Tech. A-694-8 Melpar 9.375Gc
18 Ga. Tech. A-694-9 Melpar 9.375Gc
19 Ga. Tech. A-694-10 Melpar 9.375Gc
19
17
18
16
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 79

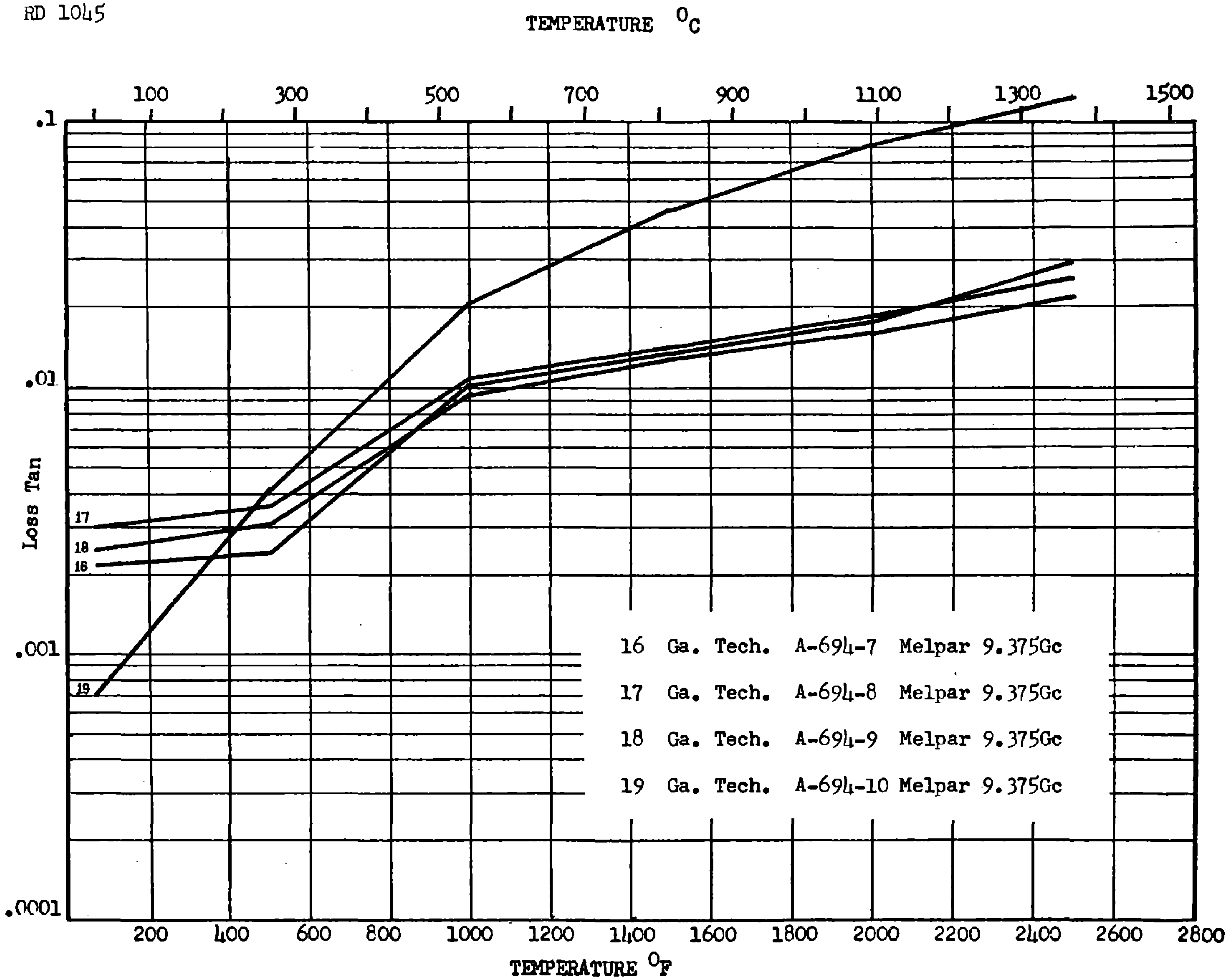

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.1
.01
.001
.0001
Loss Tan
17
18
16
19
16 Ga. Tech. A-694-7 Melpar 9.375Gc
17 Ga. Tech. A-694-8 Melpar 9.375Gc
18 Ga. Tech. A-694-9 Melpar 9.375Gc
19 Ga. Tech. A-694-10 Melpar 9.375Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 80

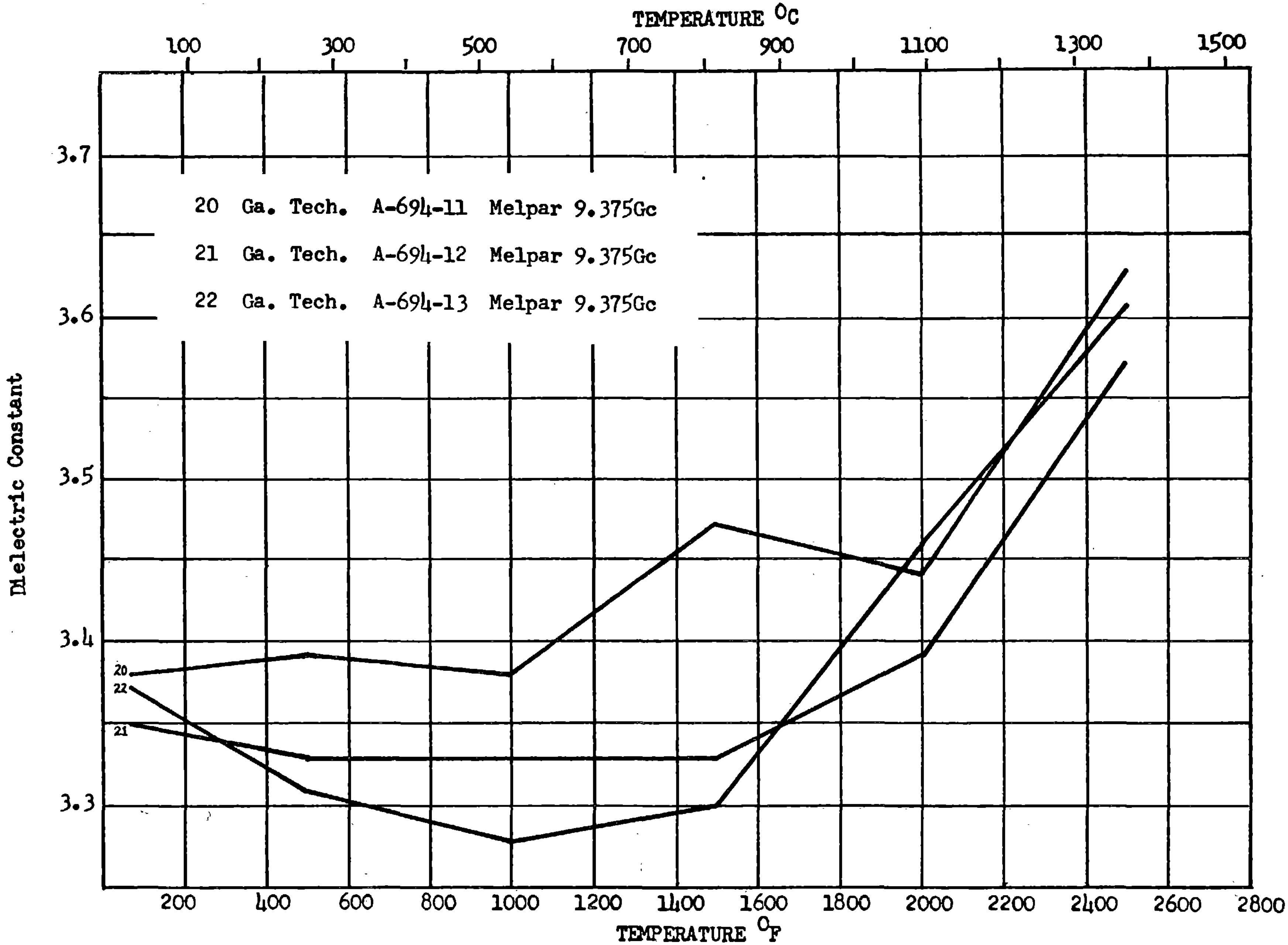

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
20 Ga. Tech. A-694-11 Melpar 9.375Gc
21 Ga. Tech. A-694-12 Melpar 9.375Gc
22 Ga. Tech. A-694-13 Melpar 9.375Gc
Dielectric Constant
3.7
3.6
3.5
3.4
3.3
20
22
21
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 81

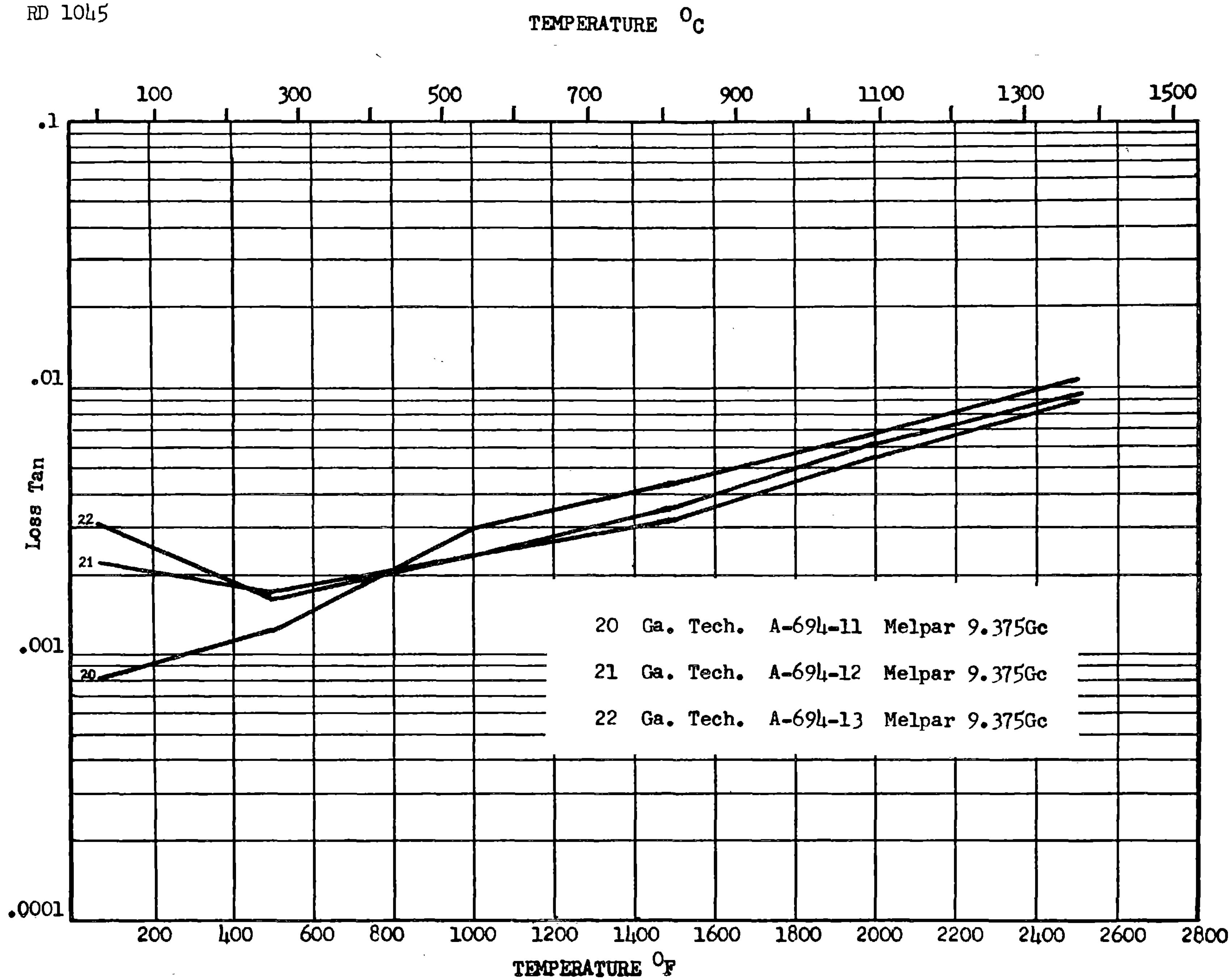

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.1
.01
.001
.0001
Loss Tan
22
21
20
20 Ga. Tech. A-694-11 Melpar 9.375Gc
21 Ga. Tech. A-694-12 Melpar 9.375Gc
22 Ga. Tech. A-694-13 Melpar 9.375Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 82

RD 1046

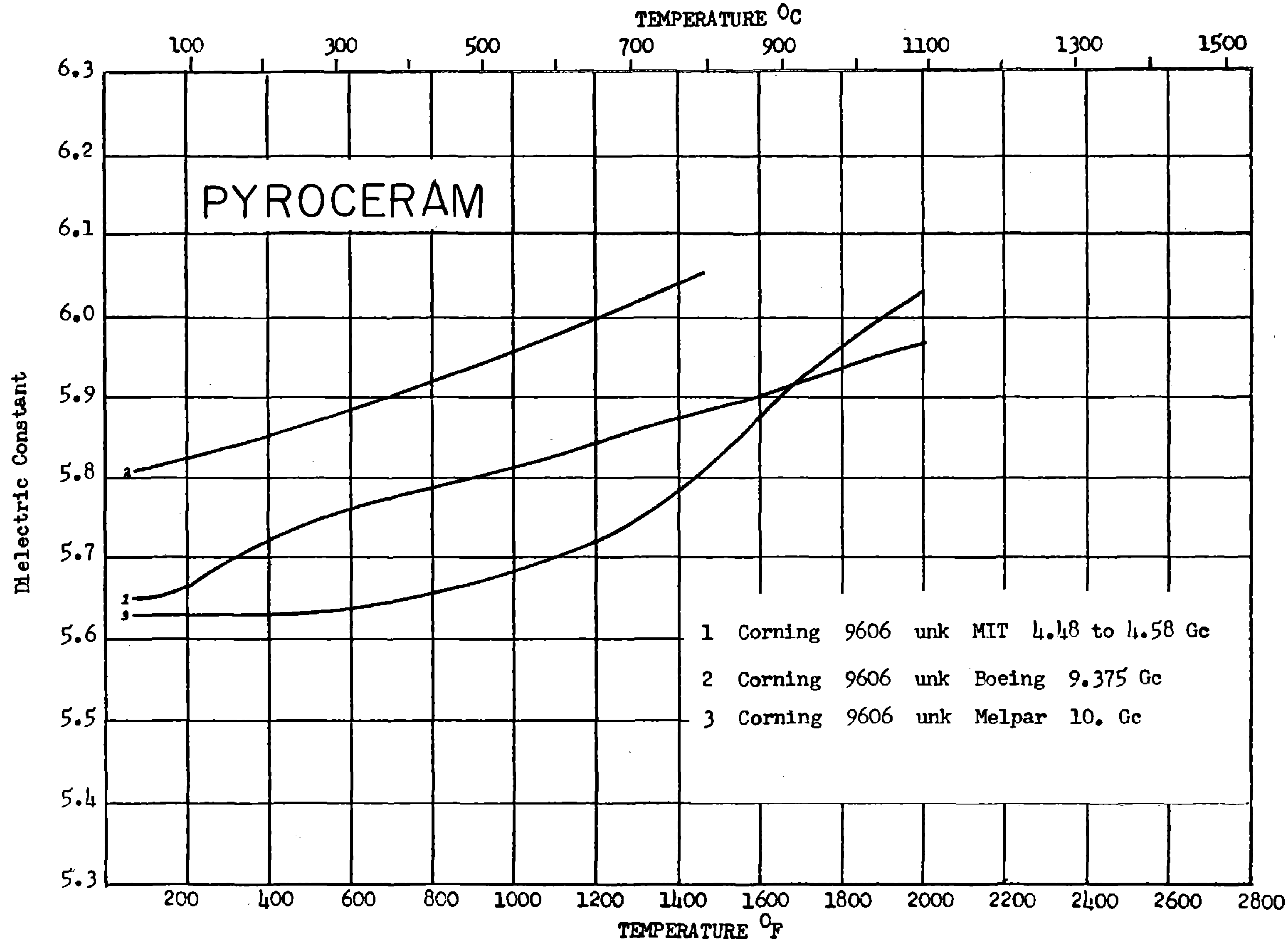


Figure 83

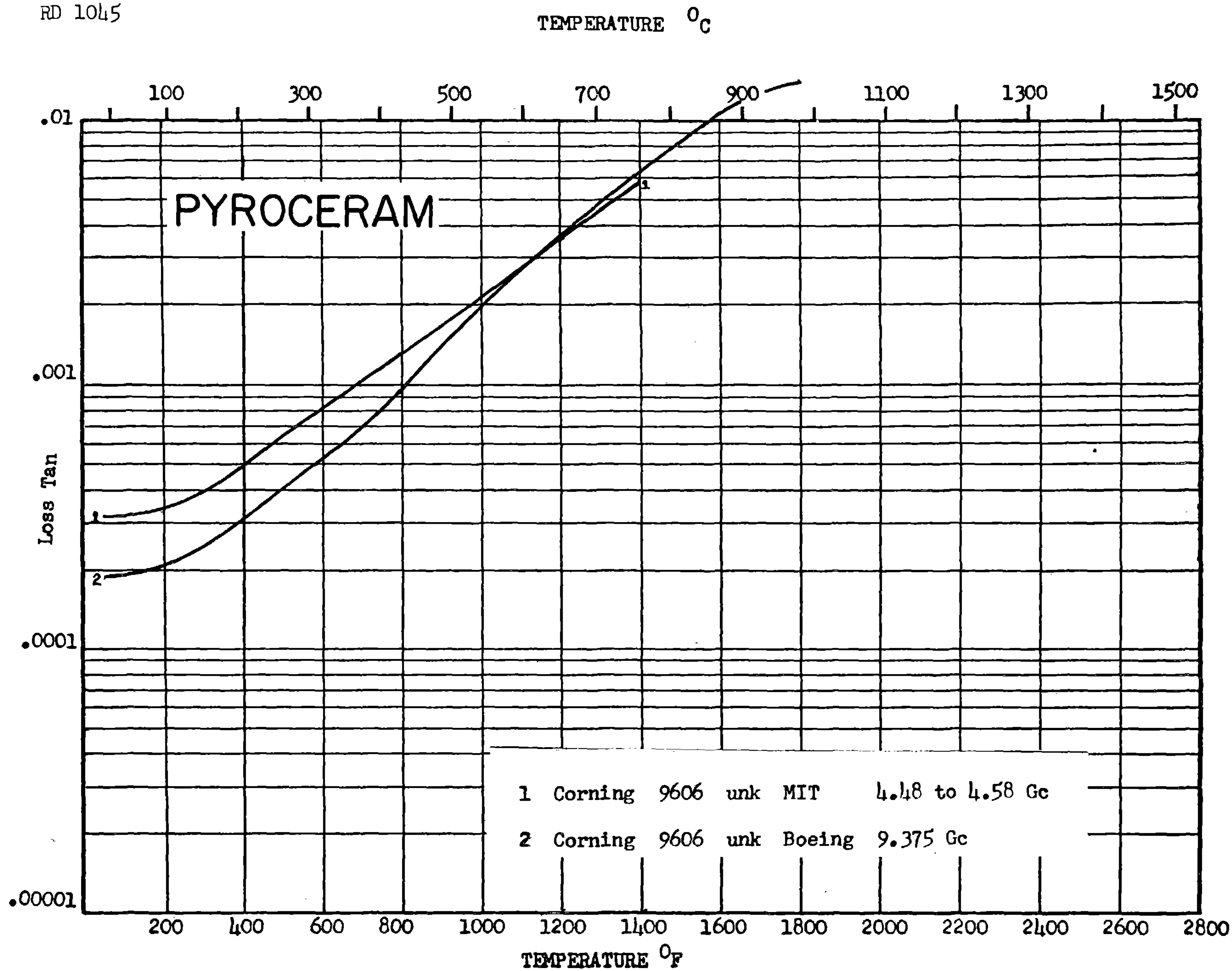

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.01
.001
.0001
.00001
Loss Tan
PYROCERAM
1 Corning 9606 unk MIT 4.48 to 4.58 Gc
2 Corning 9606 unk Boeing 9.375 Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 84

RD 1046

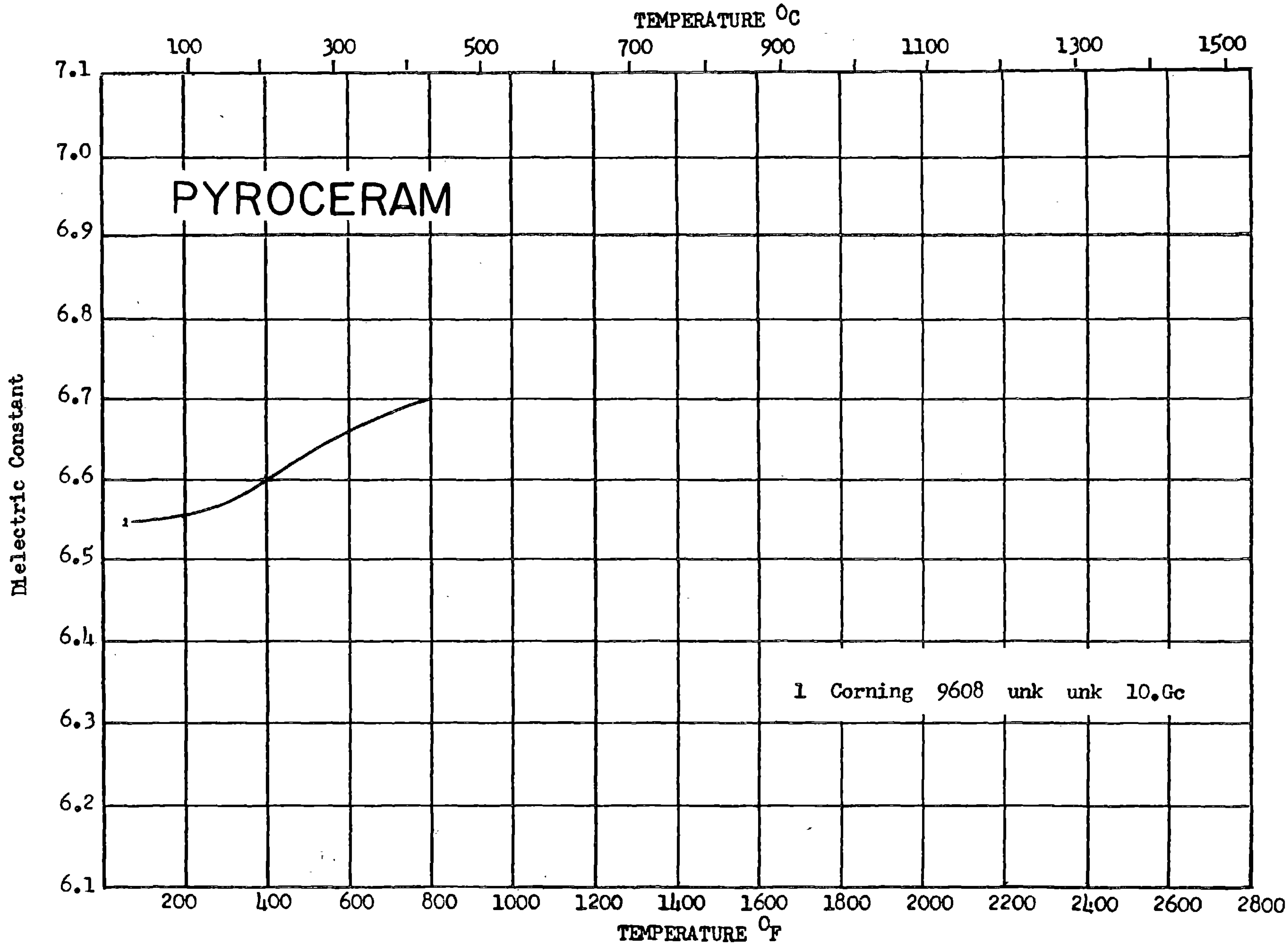


Figure 85

RD 1045

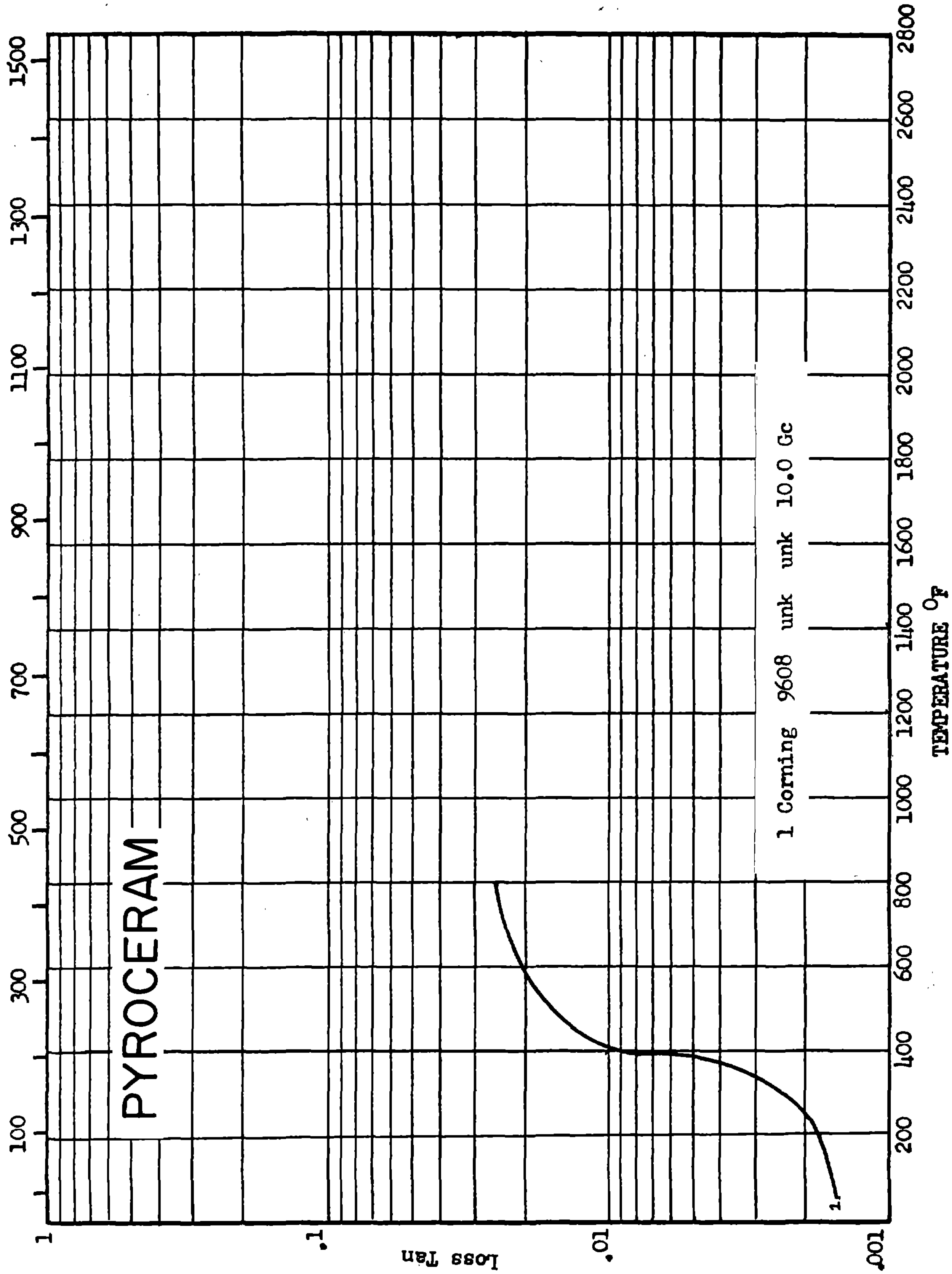
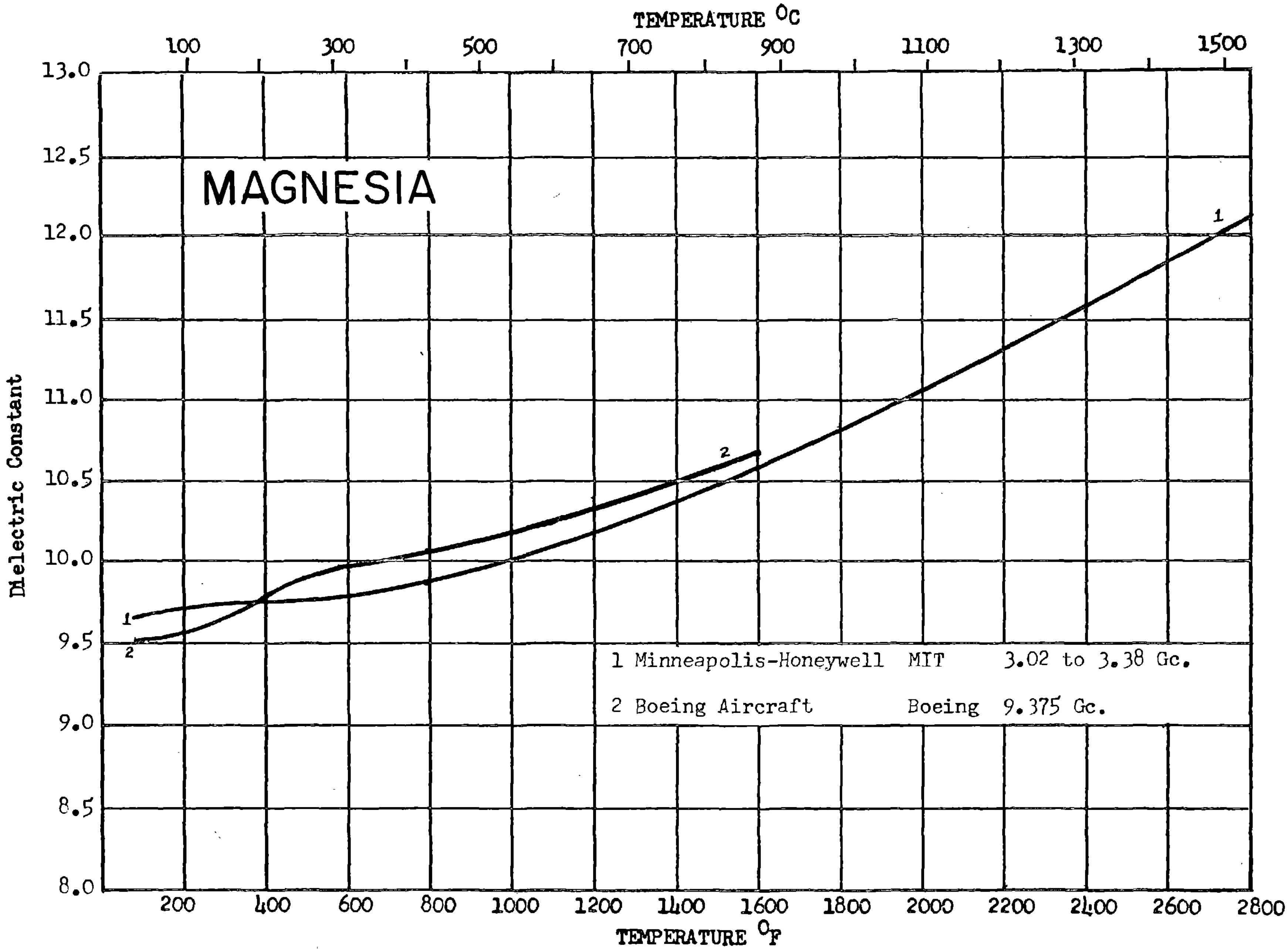


Figure 86


TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
MAGNESIA
13.0
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
Dielectric Constant
1
2
1 Minneapolis-Honeywell MIT 3.02 to 3.38 Gc.
2 Boeing Aircraft Boeing 9.375 Gc.
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F
Figure 87

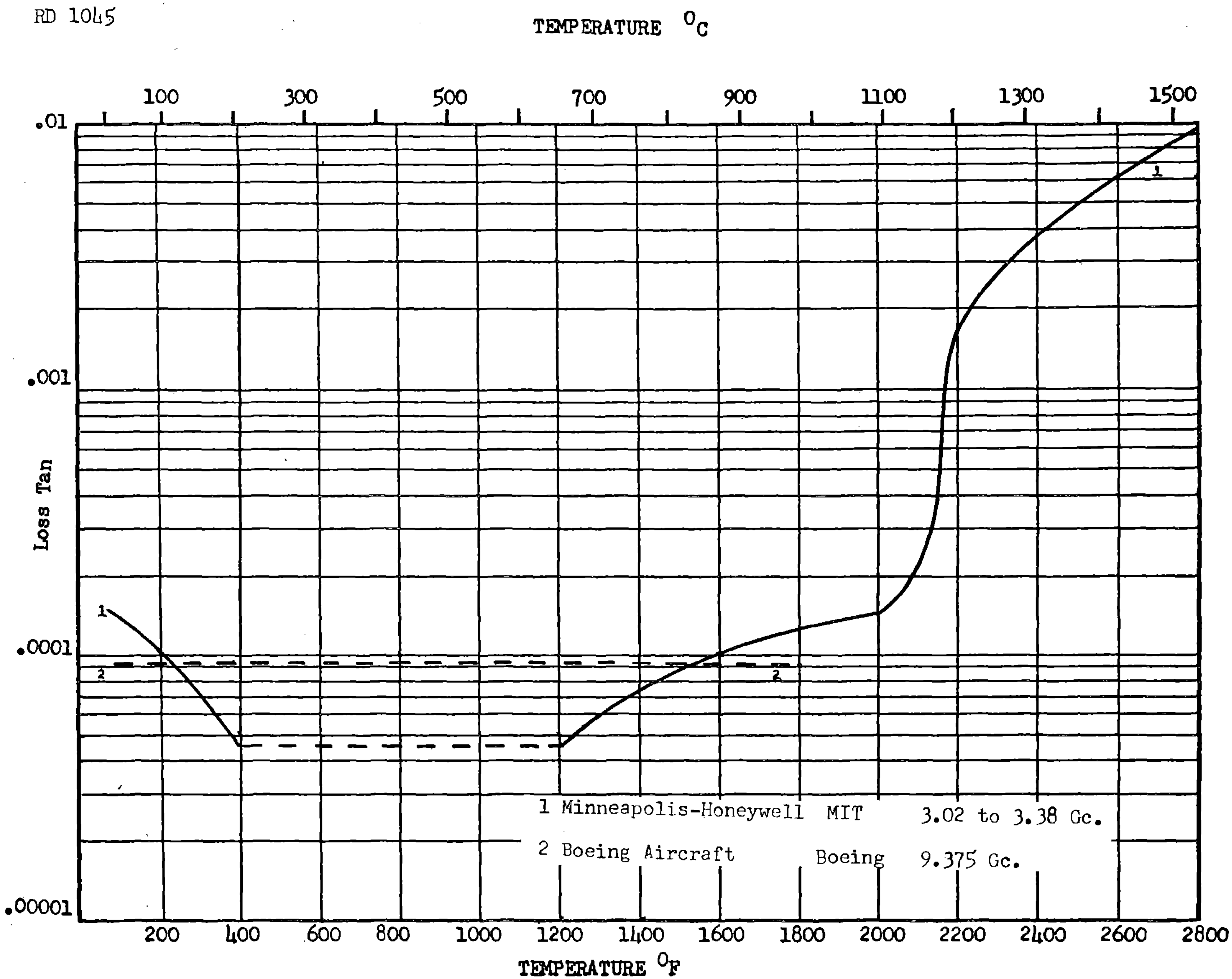

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.01
.001
.0001
.00001
Loss Tan
1
2
1 Minneapolis-Honeywell MIT 3.02 to 3.38 Gc.
2 Boeing Aircraft Boeing 9.375 Gc.
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 88

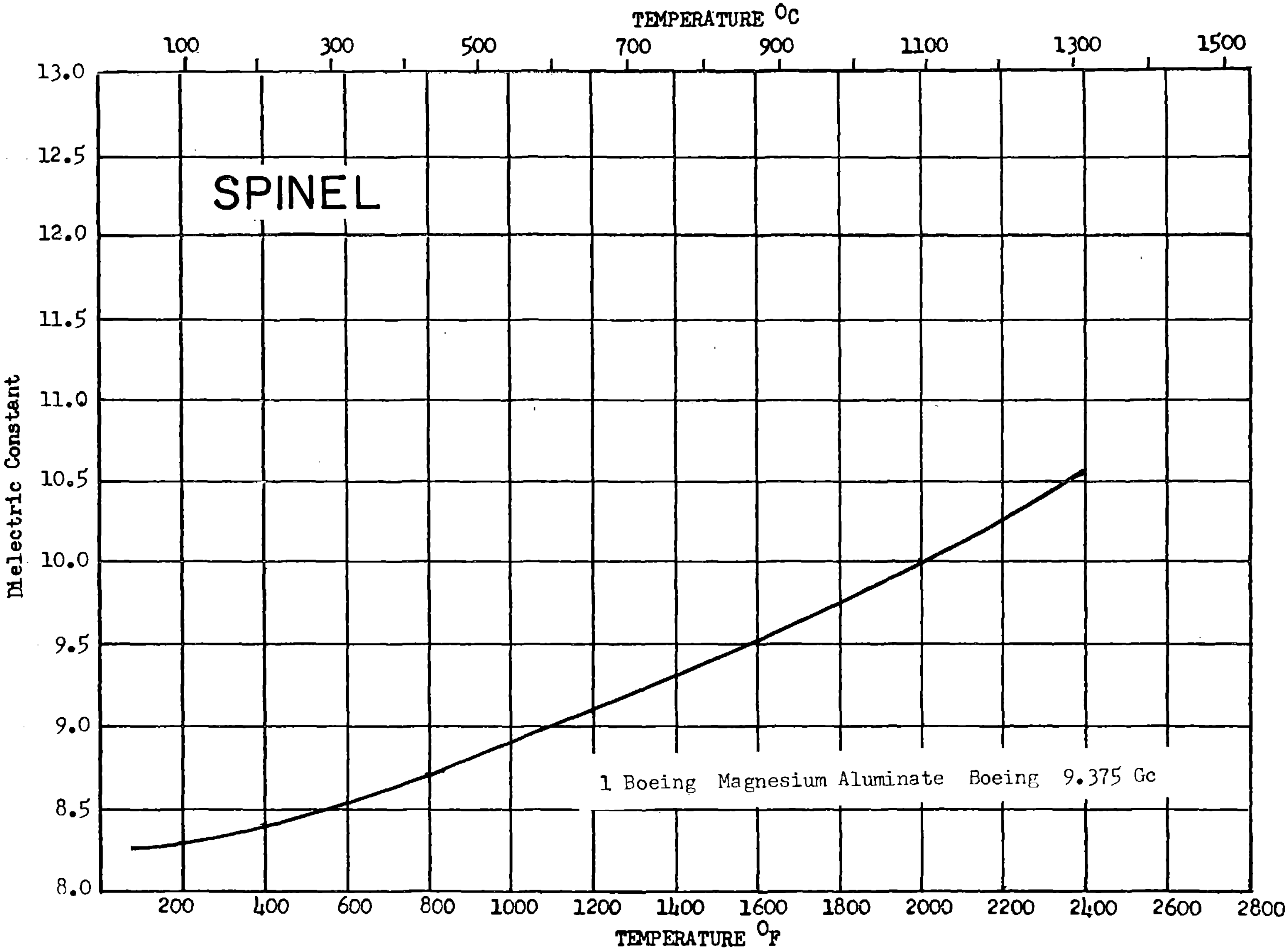

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
13.0
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
Dielectric Constant
SPINEL
1 Boeing Magnesium Aluminate Boeing 9.375 Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 89

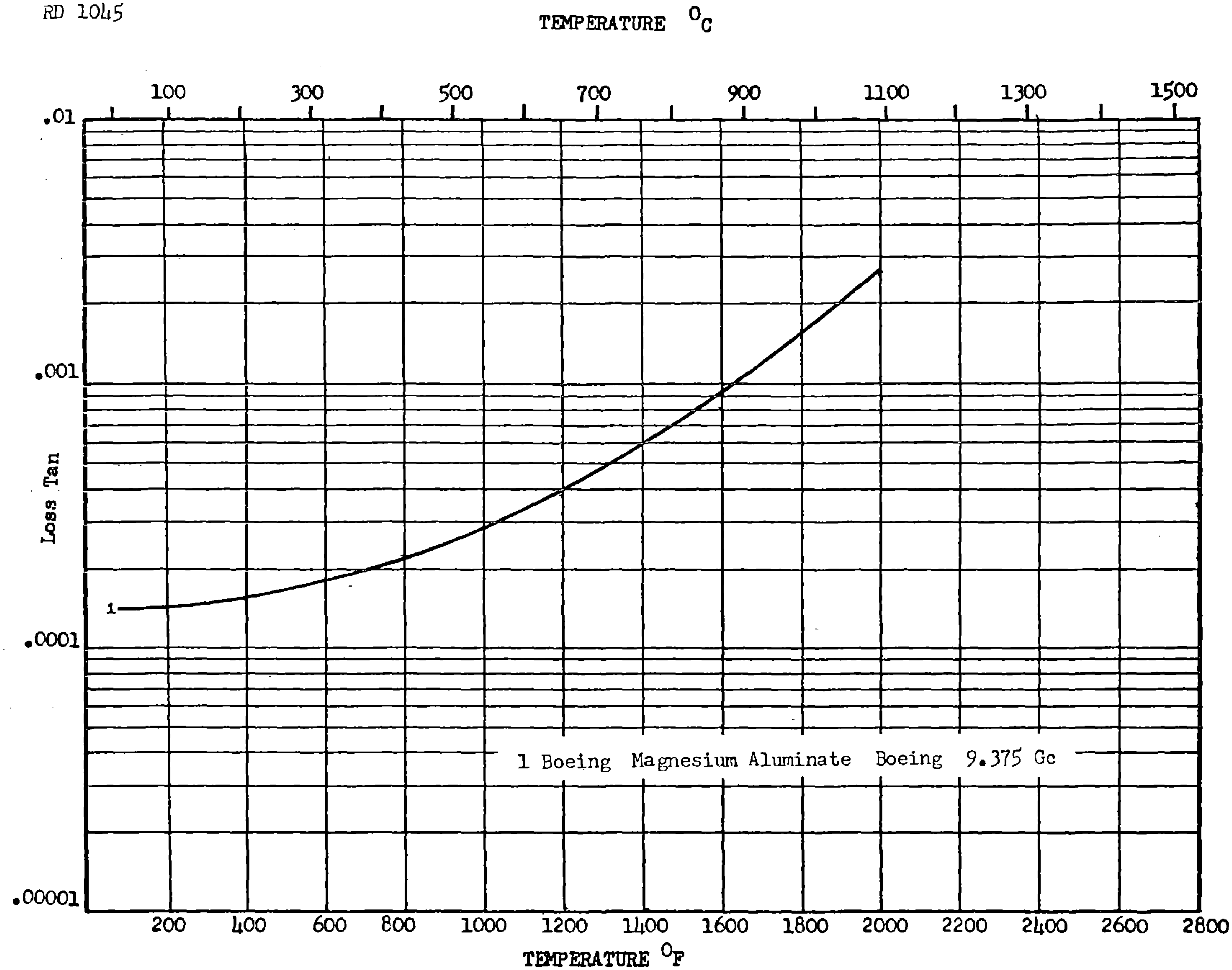

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.01
.001
.0001
.00001
Loss Tan
1
1 Boeing Magnesium Aluminate Boeing 9.375 Gc
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 90

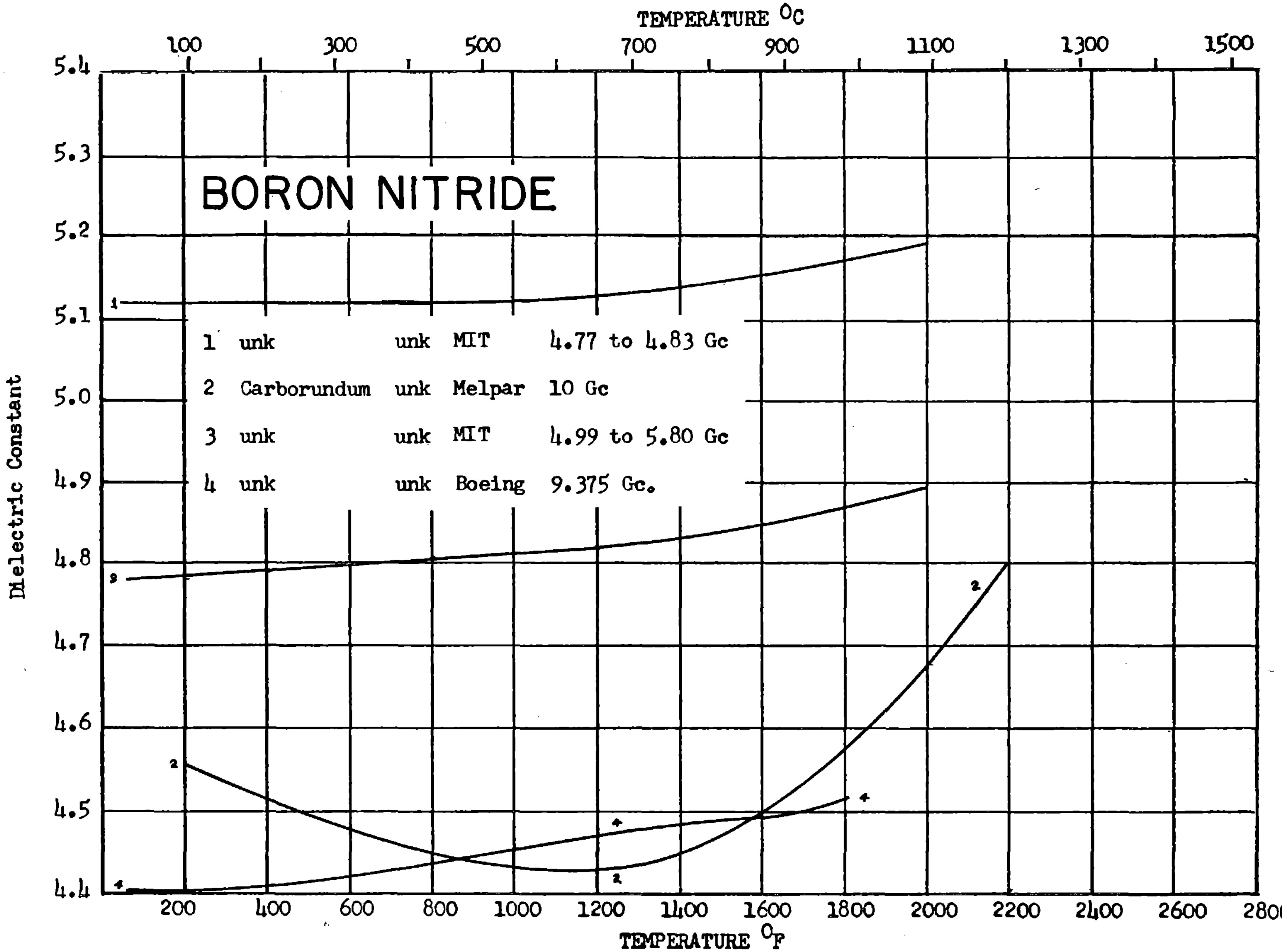

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
BORON NITRIDE
1 unk unk MIT 4.77 to 4.83 Gc
2 Carborundum unk Melpar 10 Gc
3 unk unk MIT 4.99 to 5.80 Gc
4 unk unk Boeing 9.375 Gc.
Dielectric Constant
5.4
5.3
5.2
5.1
5.0
4.9
4.8
4.7
4.6
4.5
4.4
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 91

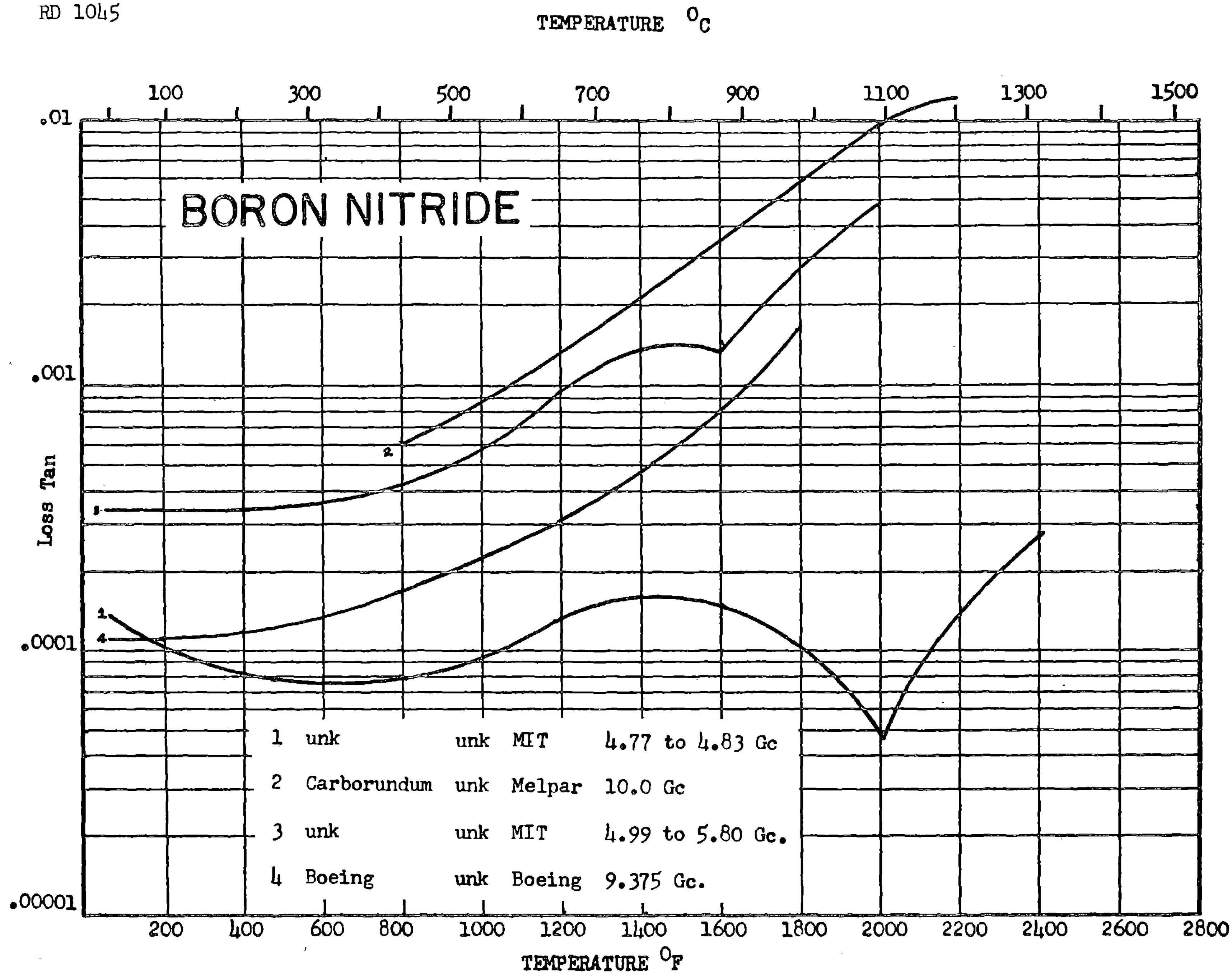

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.01
.001
.0001
.00001
Loss Tan
BORON NITRIDE
1 unk unk MIT 4.77 to 4.83 Gc
2 Carborundum unk Melpar 10.0 Gc
3 unk unk MIT 4.99 to 5.80 Gc.
4 Boeing unk Boeing 9.375 Gc.
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 92

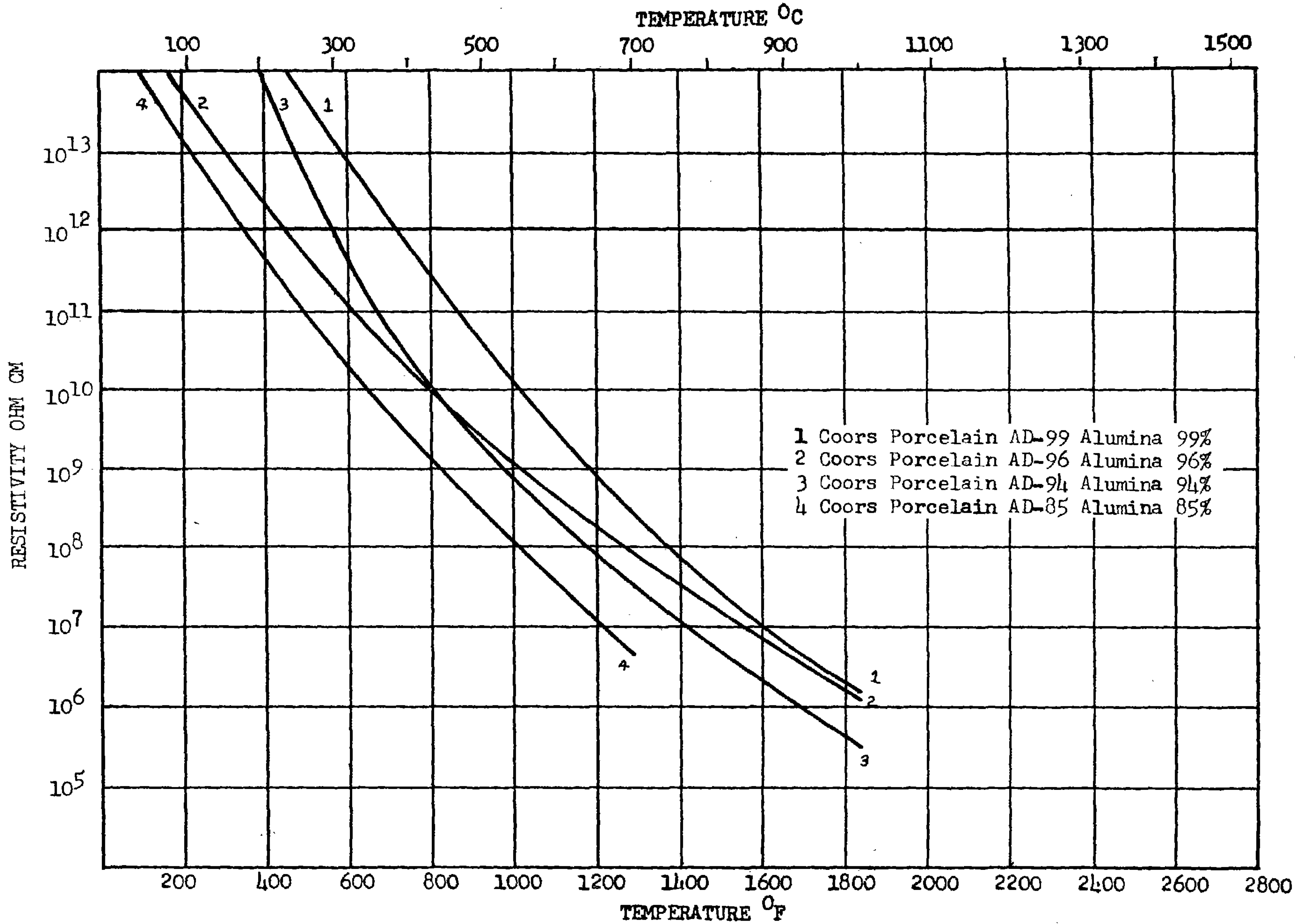

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
RESISTIVITY OHM CM
10^13
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
1 Coors Porcelain AD-99 Alumina 99%
2 Coors Porcelain AD-96 Alumina 96%
3 Coors Porcelain AD-94 Alumina 94%
4 Coors Porcelain AD-85 Alumina 85%
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 93

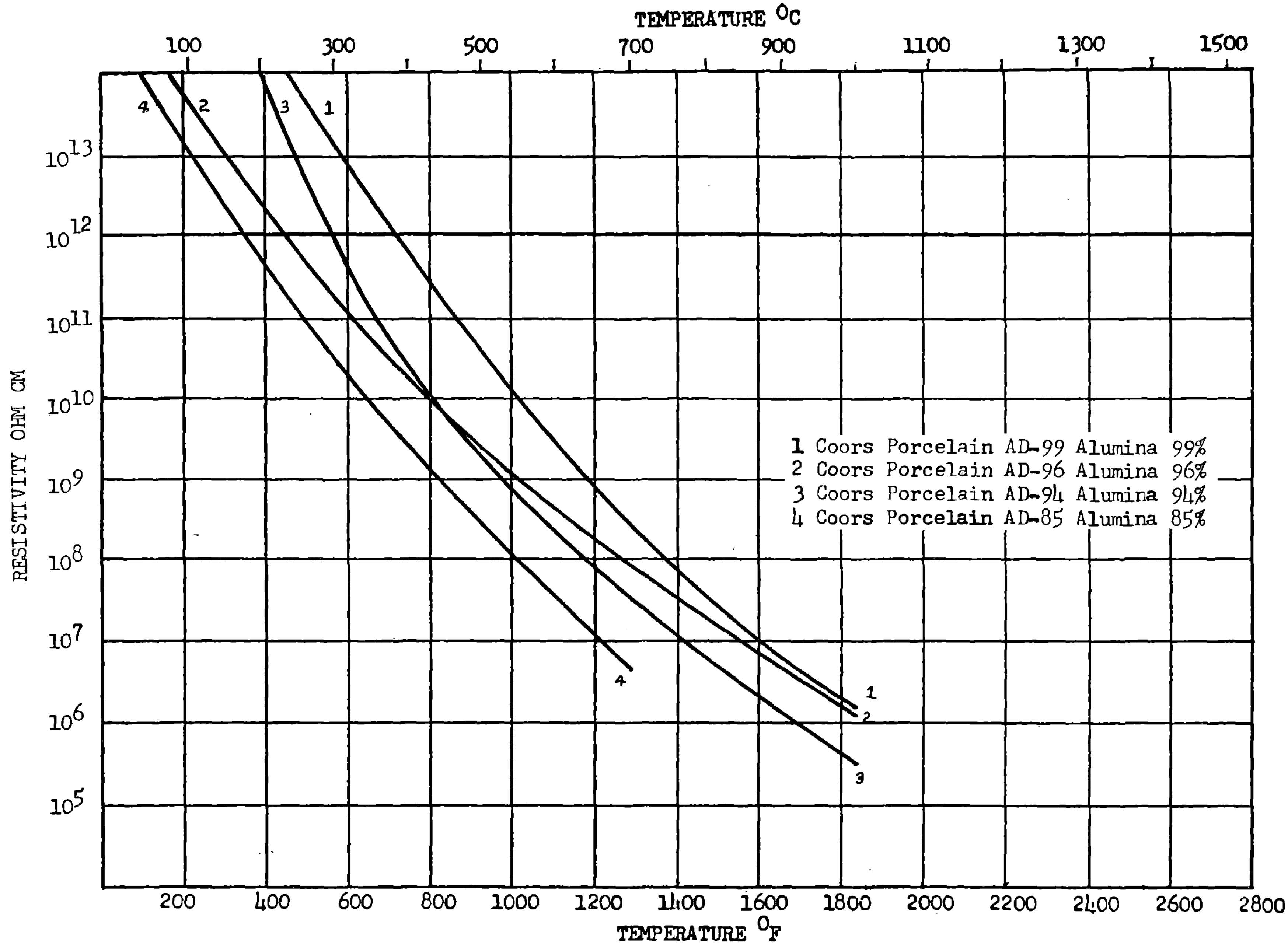

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
RESISTIVITY OHM CM
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
1 Coors Porcelain AD-99 Alumina 99%
2 Coors Porcelain AD-96 Alumina 96%
3 Coors Porcelain AD-94 Alumina 94%
4 Coors Porcelain AD-85 Alumina 85%
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 93

RD 1046

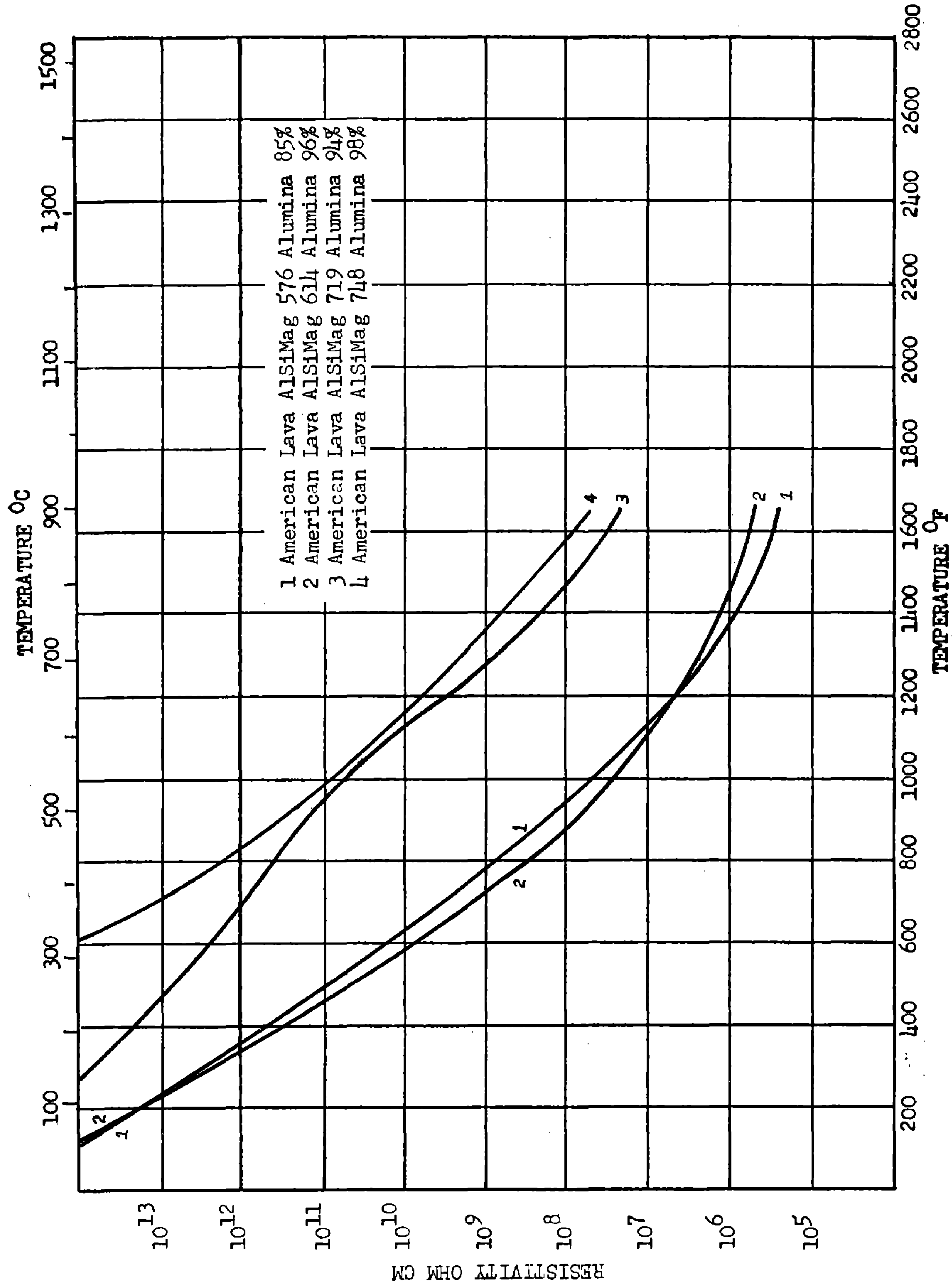


Figure 94

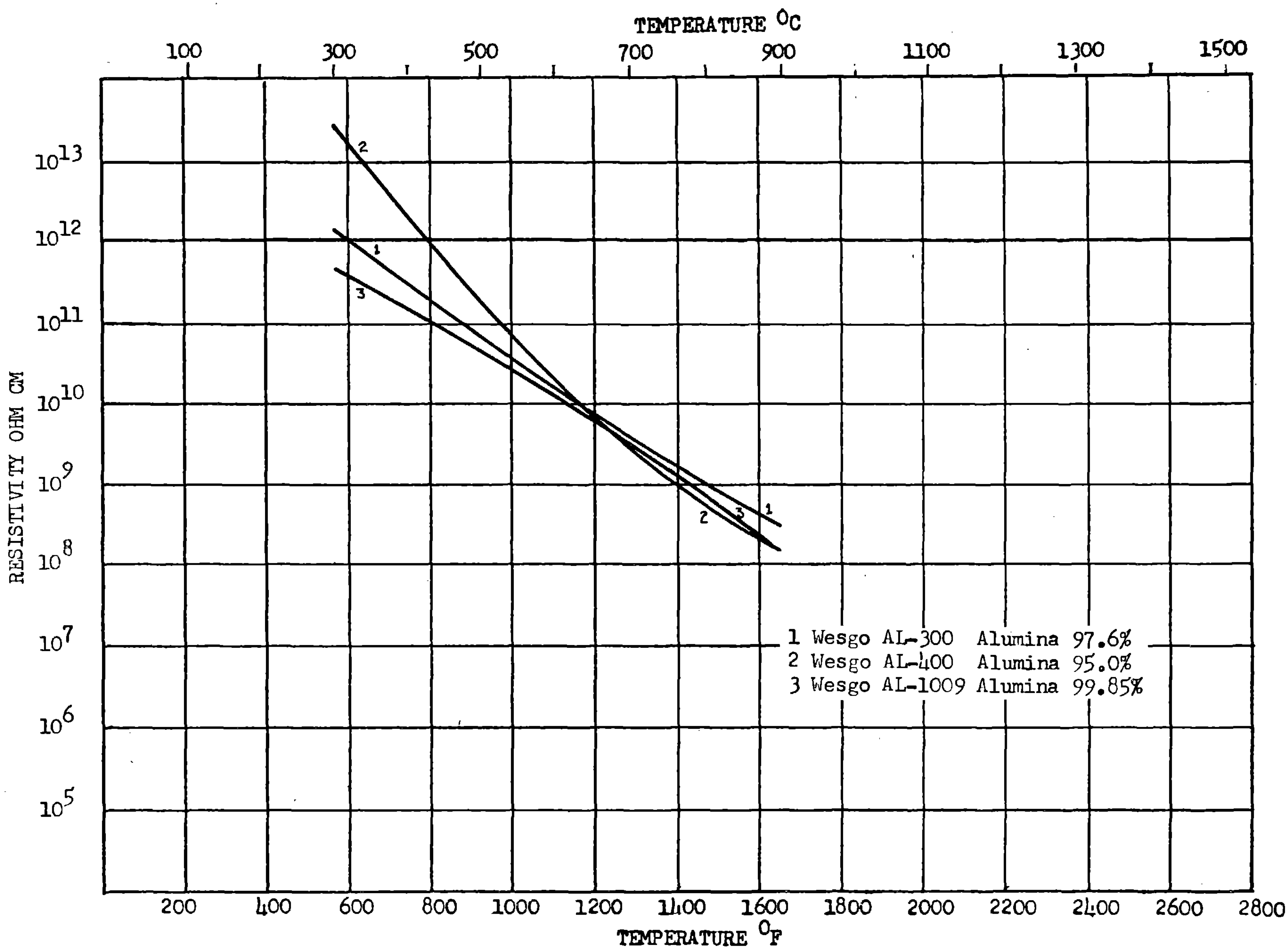

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
RESISTIVITY OHM CM
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
1 Wesgo AL-300 Alumina 97.6%
2 Wesgo AL-400 Alumina 95.0%
3 Wesgo AL-1009 Alumina 99.85%
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 95

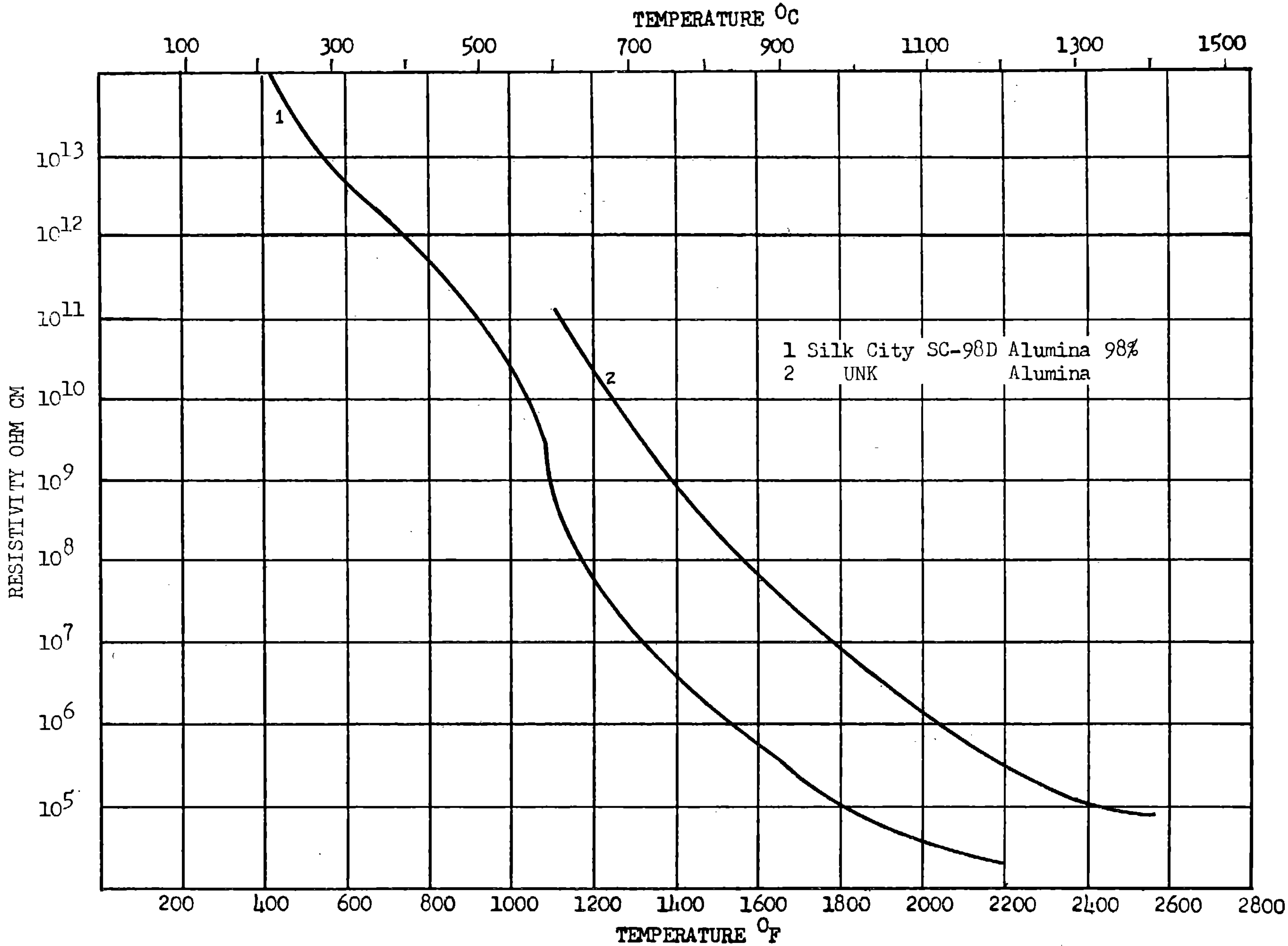

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
RESISTIVITY OHM CM
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
1
2
1 Silk City SC-98D Alumina 98%
2 UNK Alumina
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 96

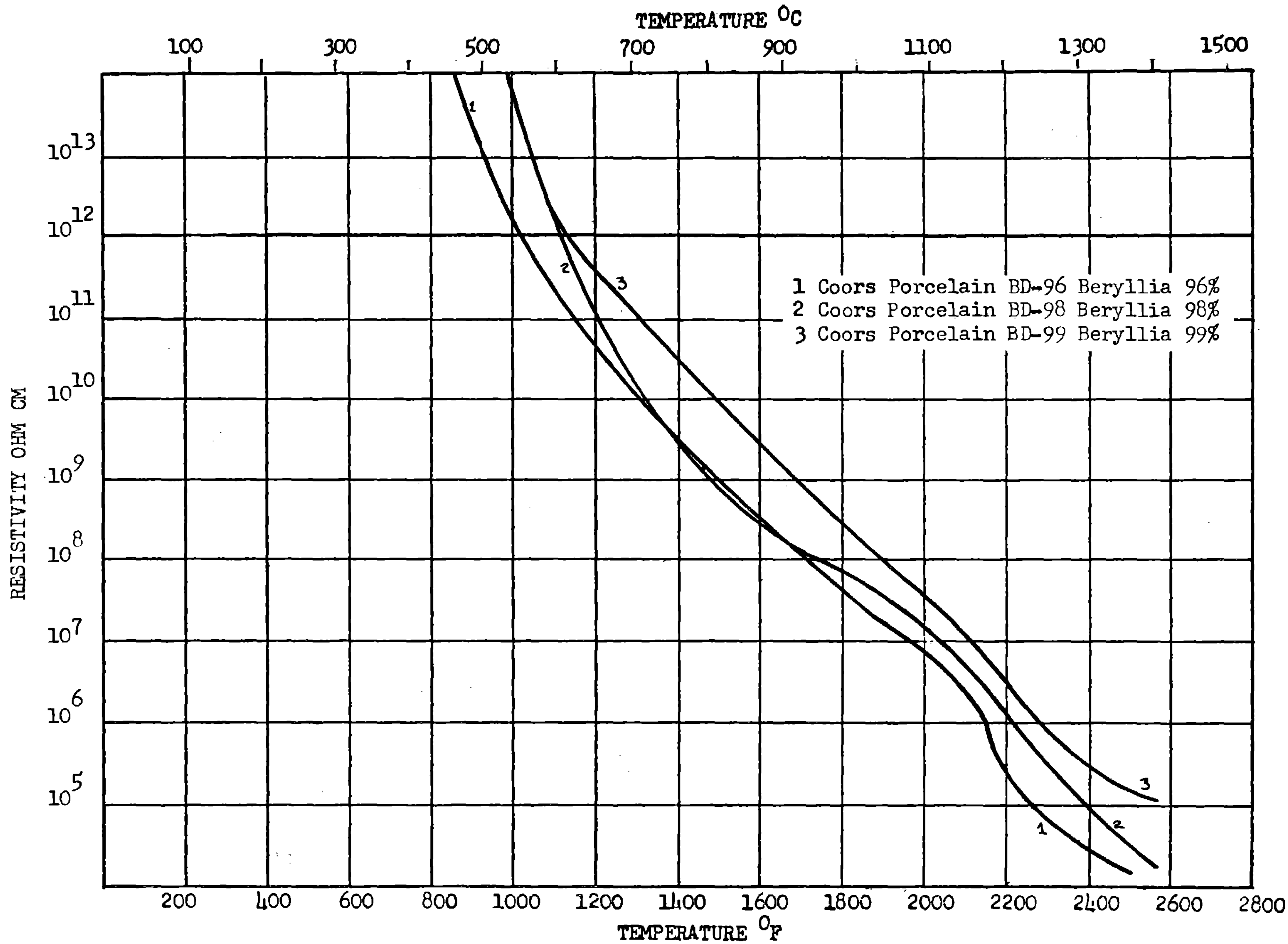

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
RESISTIVITY OHM CM
1 Coors Porcelain BD-96 Beryllia 96%
2 Coors Porcelain BD-98 Beryllia 98%
3 Coors Porcelain BD-99 Beryllia 99%
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 97

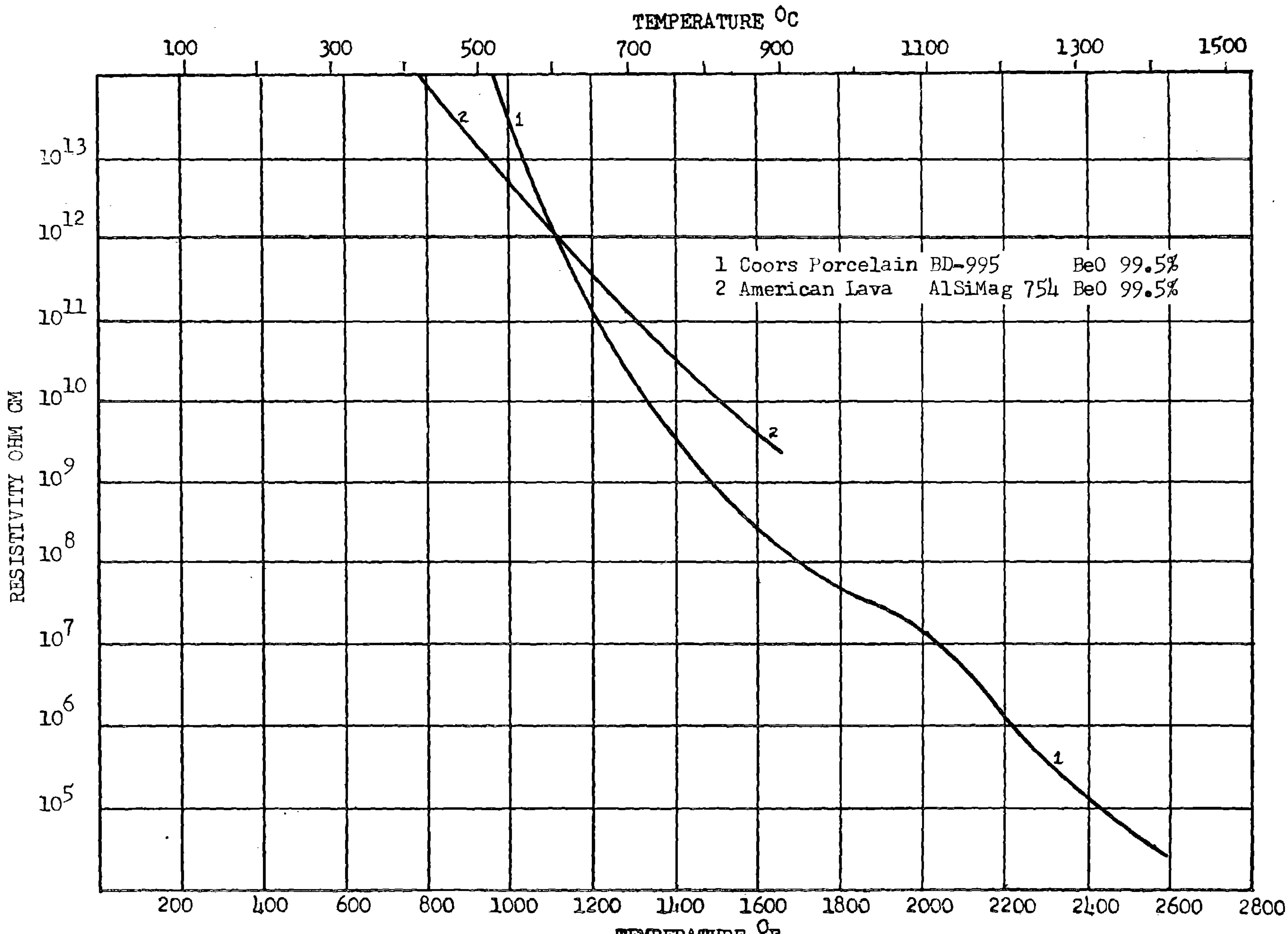

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
1 Coors Porcelain BD-995 BeO 99.5%
2 American Lava AlSiMag 754 BeO 99.5%
RESISTIVITY OHM CM
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F
1
2

Figure 98

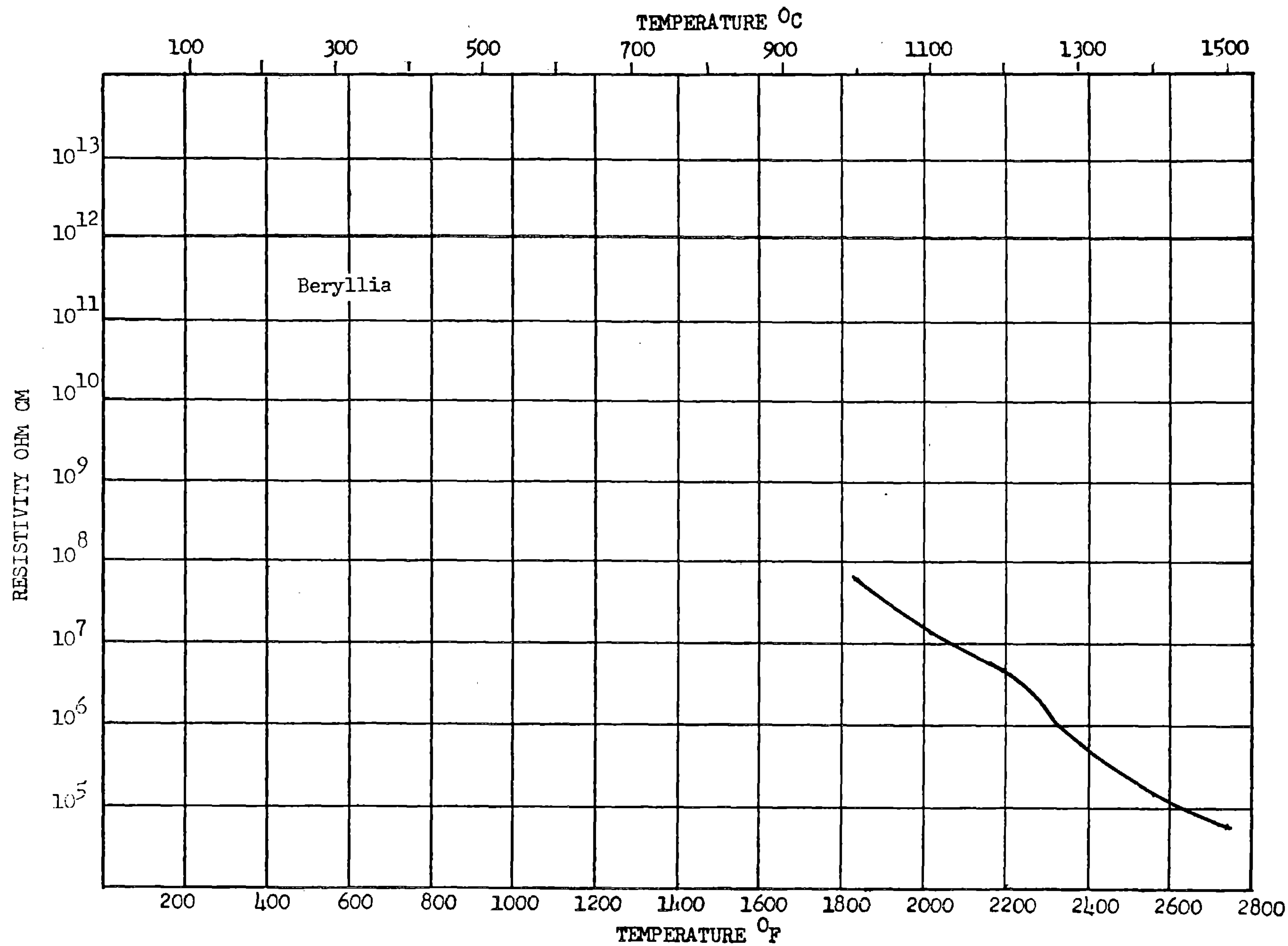

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
Beryllia
RESISTIVITY OHM CM
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 99

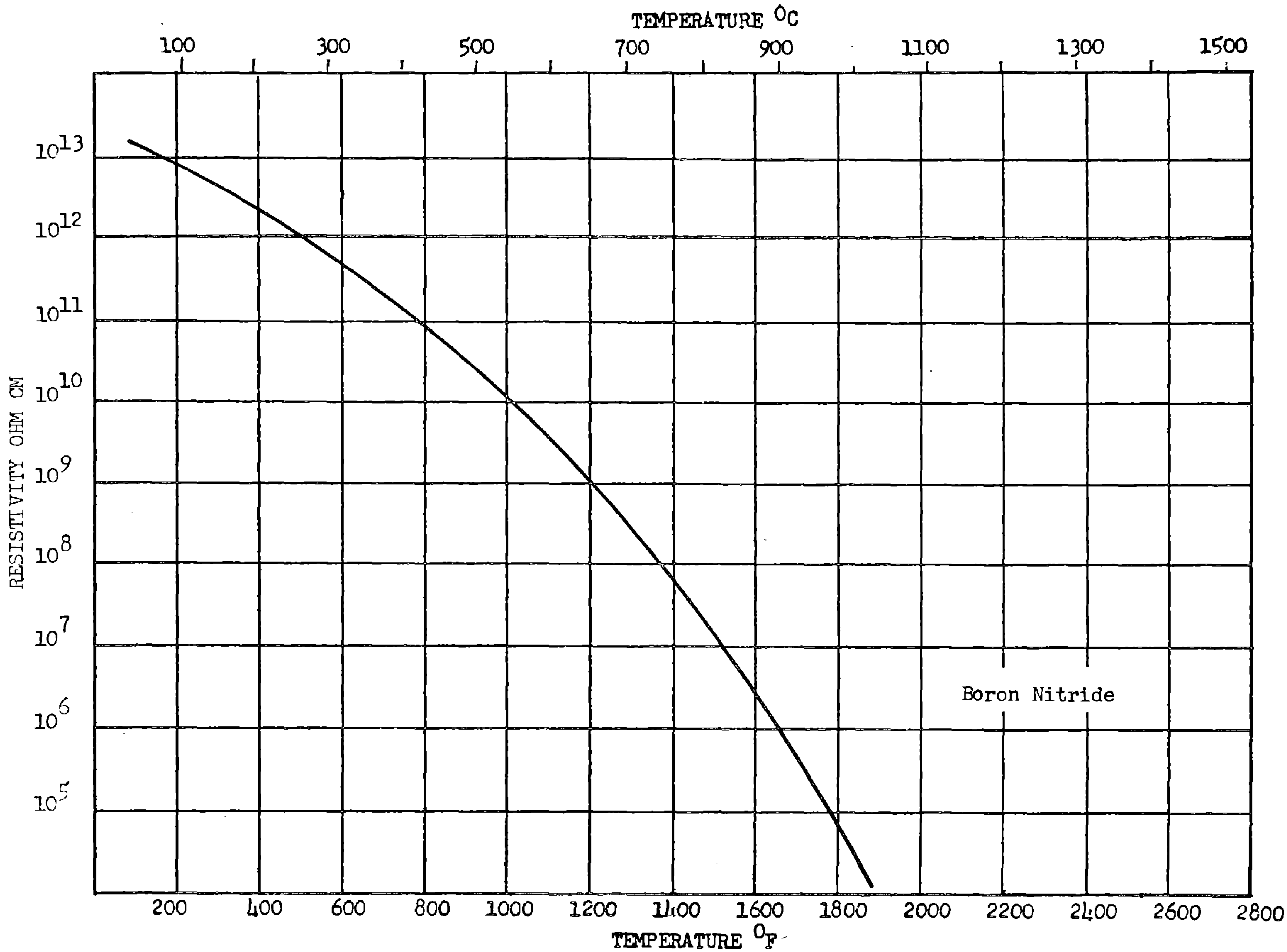

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
RESISTIVITY OHM CM
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
Boron Nitride
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 100

RD 1046

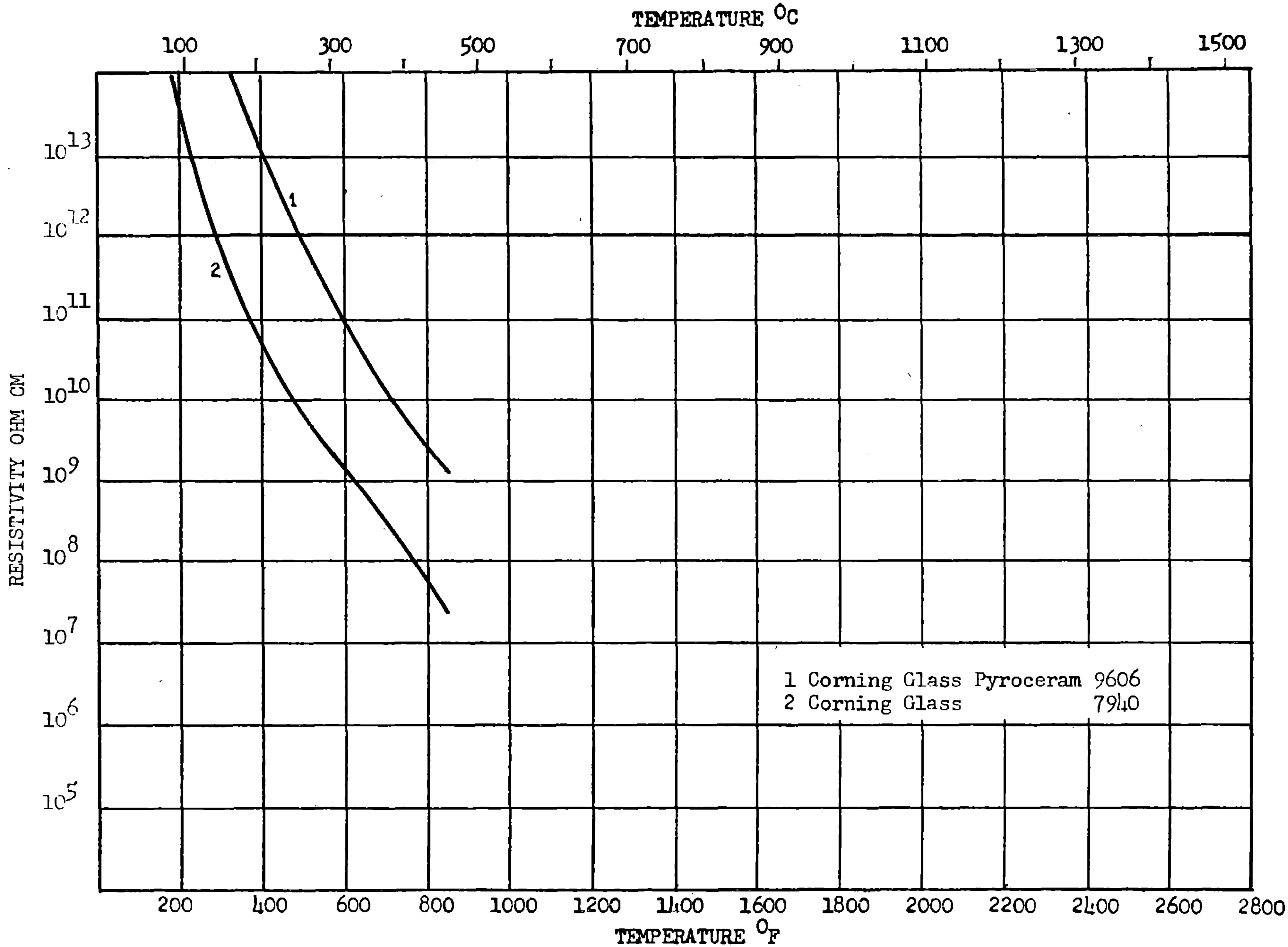


Figure 101

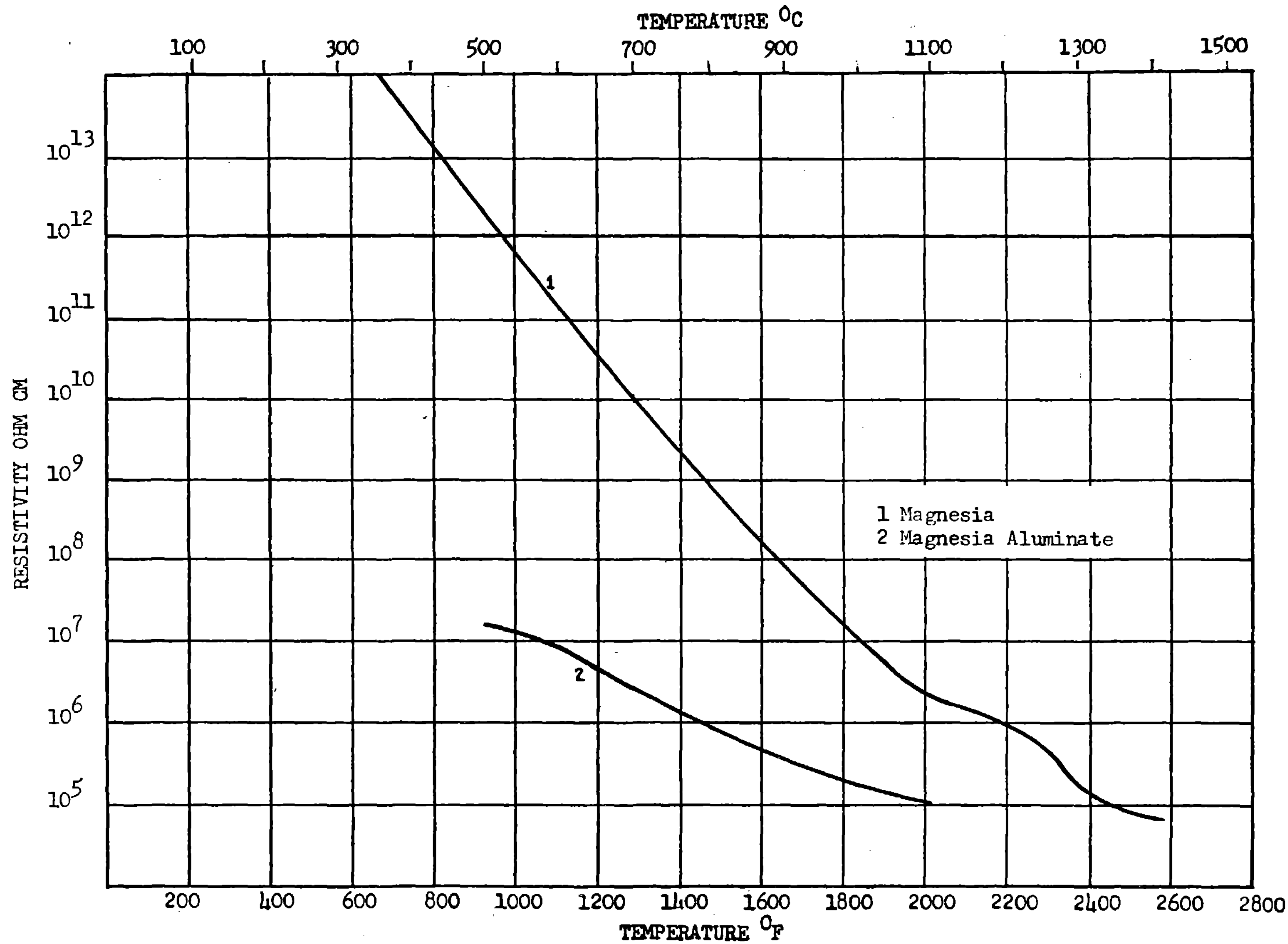

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
RESISTIVITY OHM CM
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
1
2
1 Magnesia
2 Magnesia Aluminate
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 102

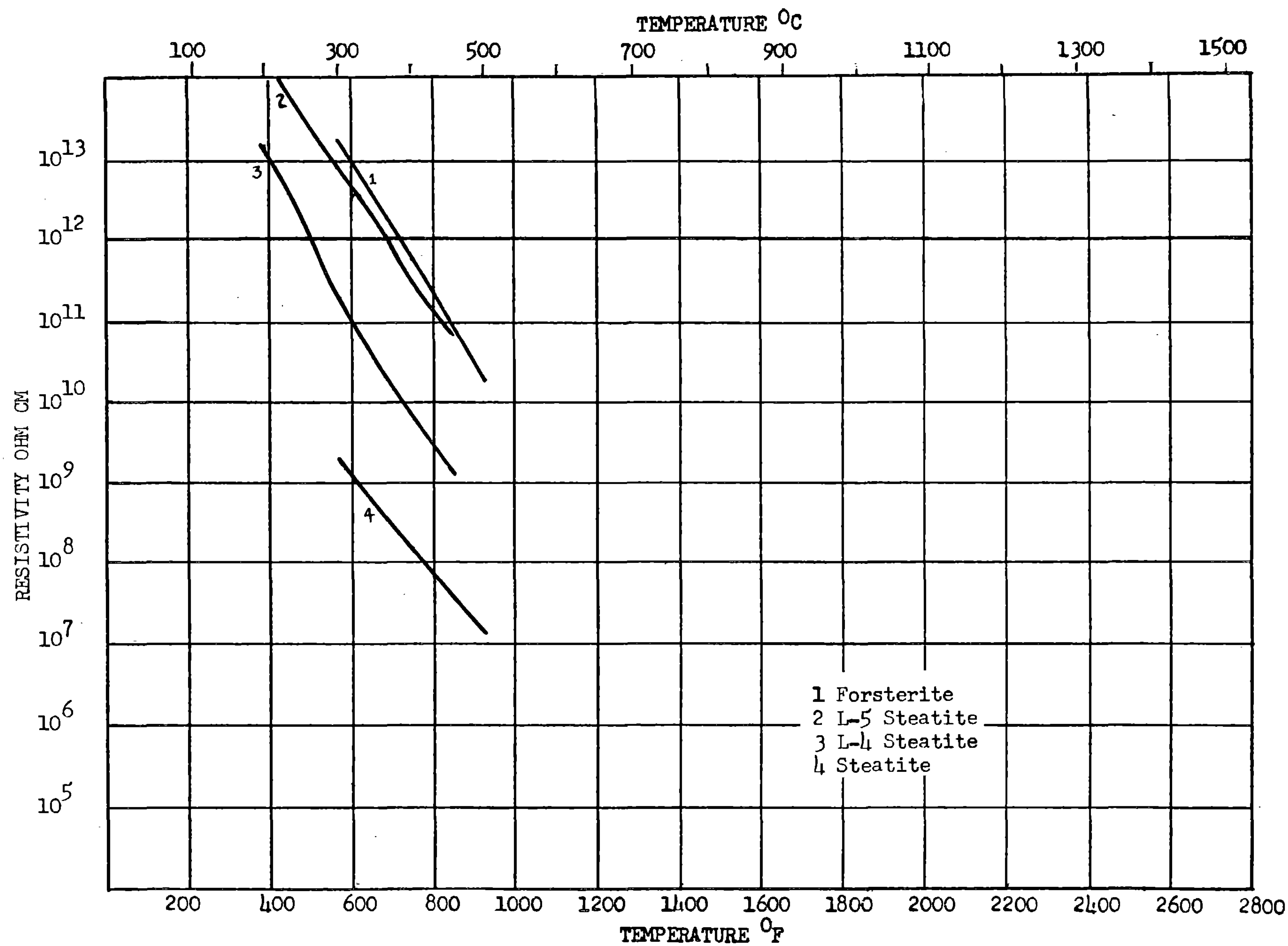

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
RESISTIVITY OHM CM
10^13
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
1
2
3
4
1 Forsterite
2 L-5 Steatite
3 L-4 Steatite
4 Steatite
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 103

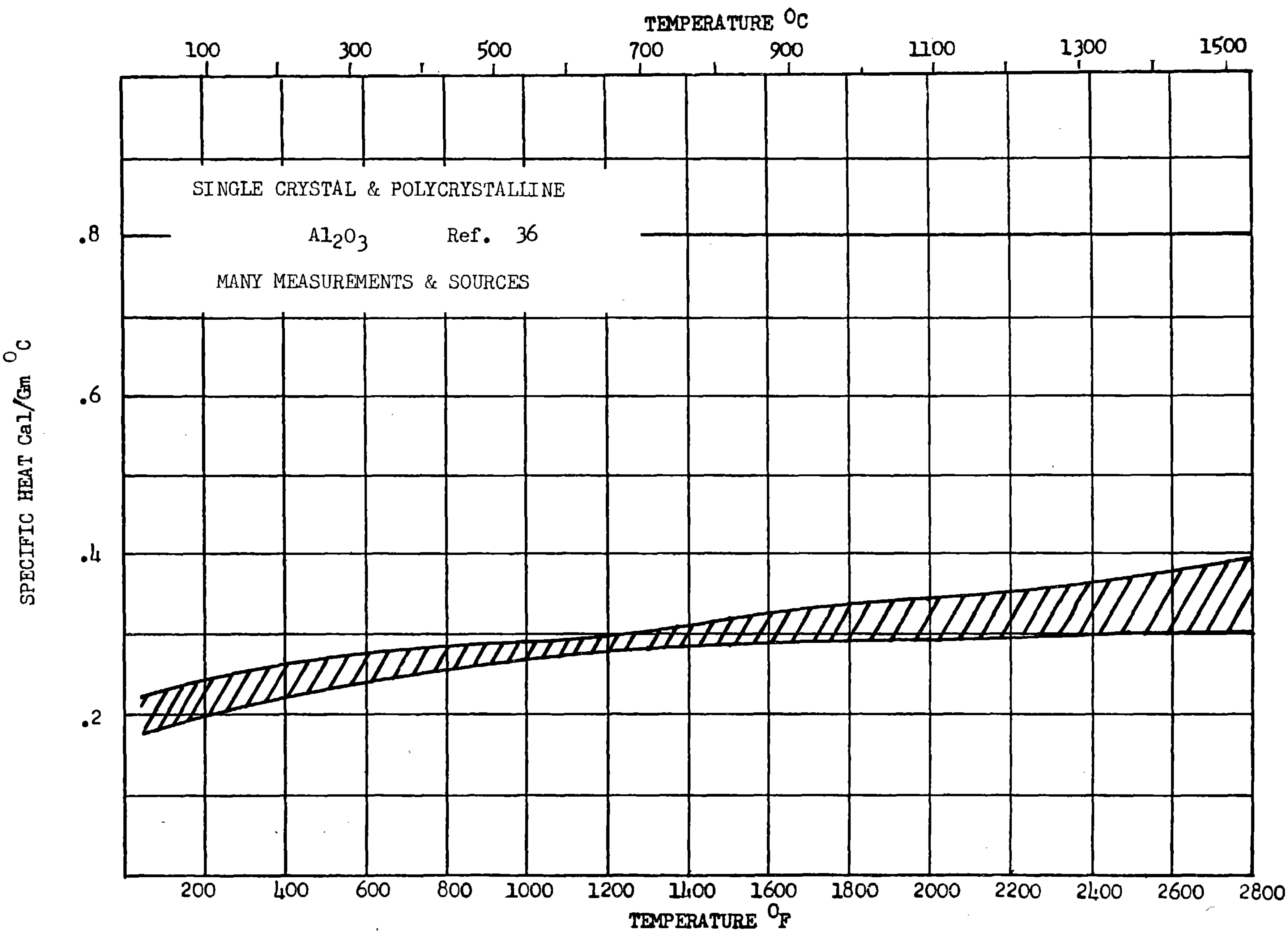

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
SINGLE CRYSTAL & POLYCRYSTALLINE
Al2O3 Ref. 36
MANY MEASUREMENTS & SOURCES
SPECIFIC HEAT Cal/Gm °C
.8
.6
.4
.2
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 104

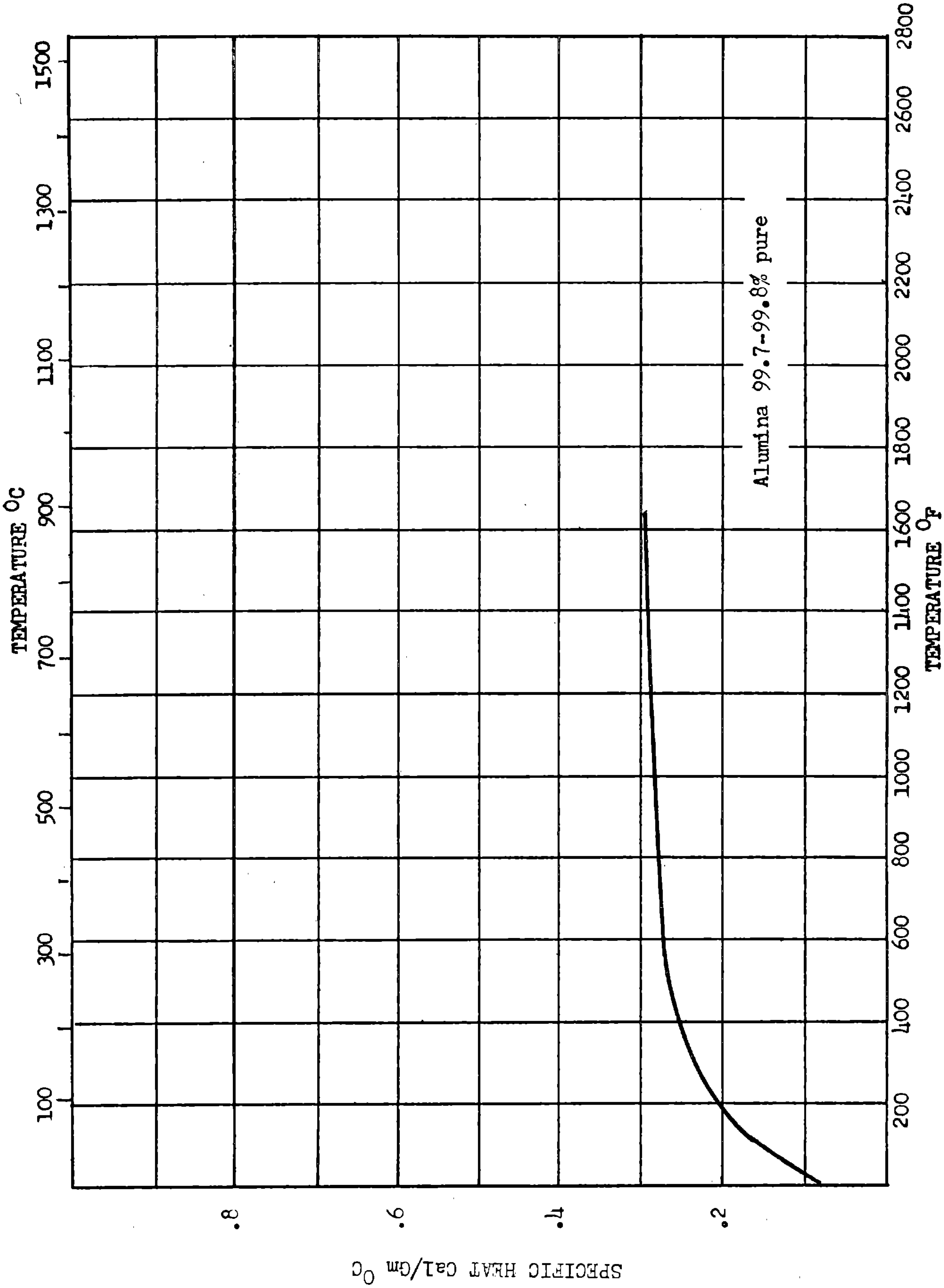

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
TEMPERATURE °F
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
SPECIFIC HEAT Cal/Gm °C
.2
.4
.6
.8
Alumina 99.7-99.8% pure

Figure 105

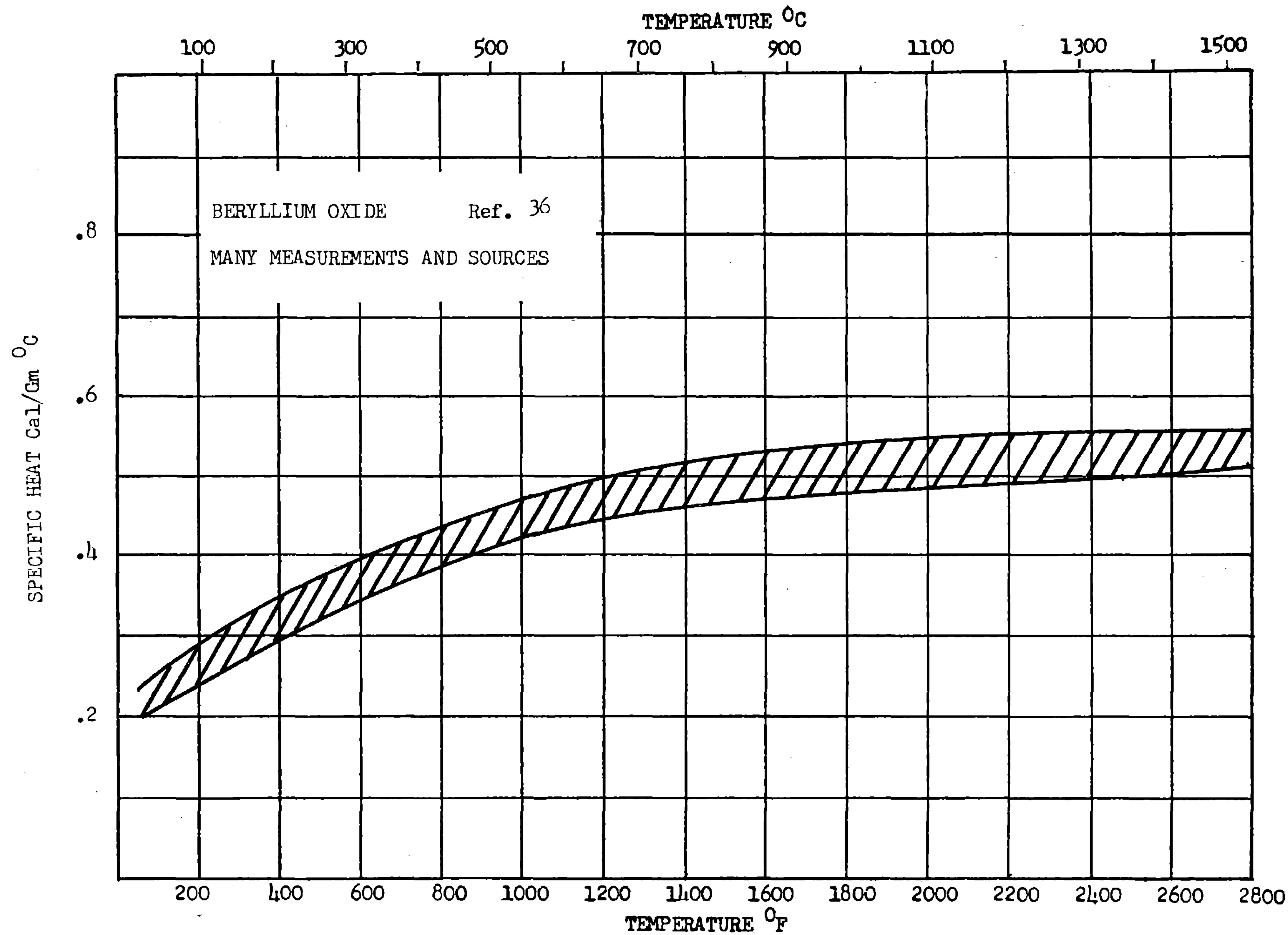

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
BERYLLIUM OXIDE Ref. 36
MANY MEASUREMENTS AND SOURCES
SPECIFIC HEAT Cal/Gm °C
.8
.6
.4
.2
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 106

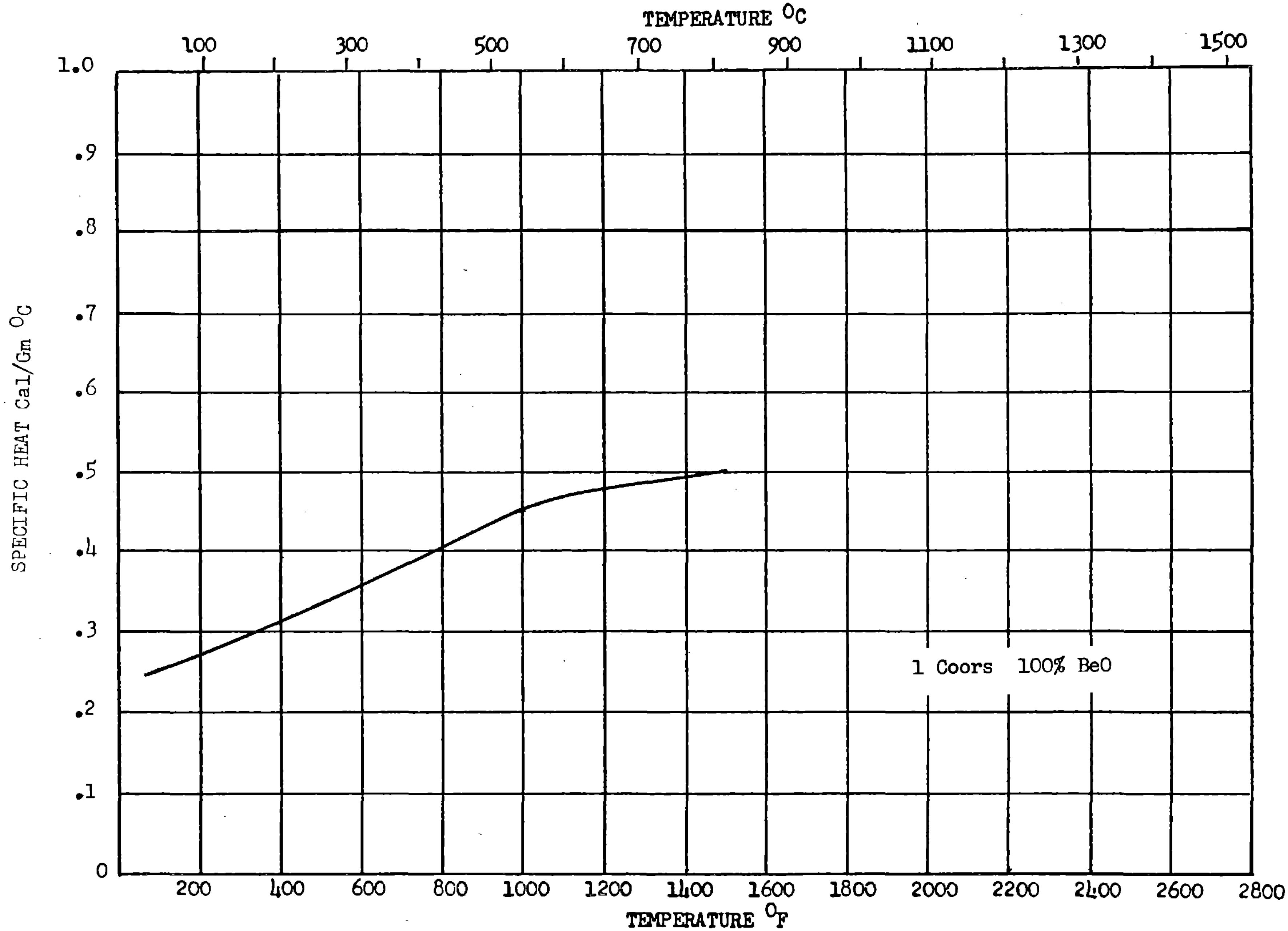

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
SPECIFIC HEAT Cal/Gm °C
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
1 Coors 100% BeO
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 107

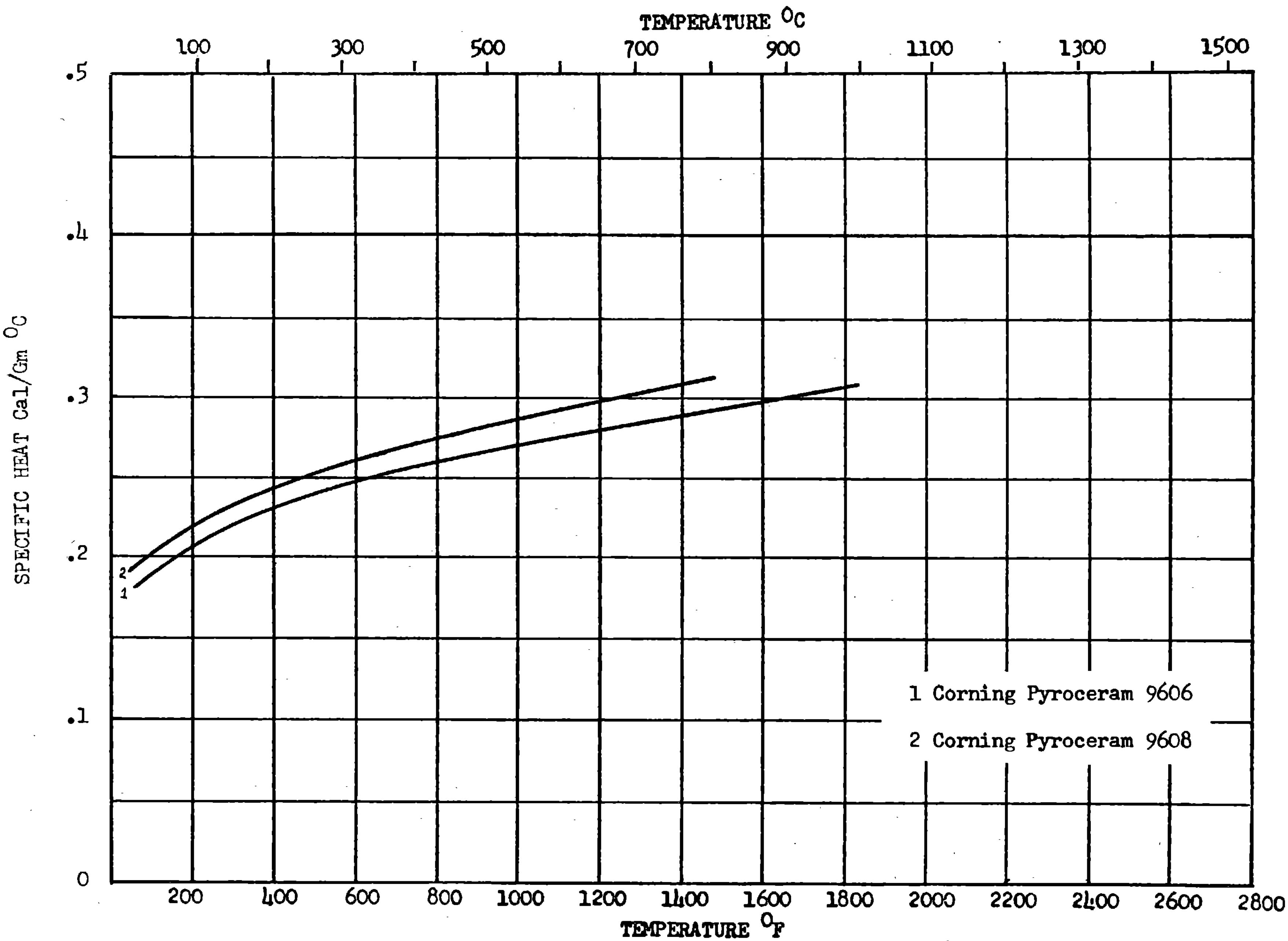

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
SPECIFIC HEAT Cal/Gm °C
.5
.4
.3
.2
.1
0
2
1
1 Corning Pyroceram 9606
2 Corning Pyroceram 9608
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 108

RD 1046

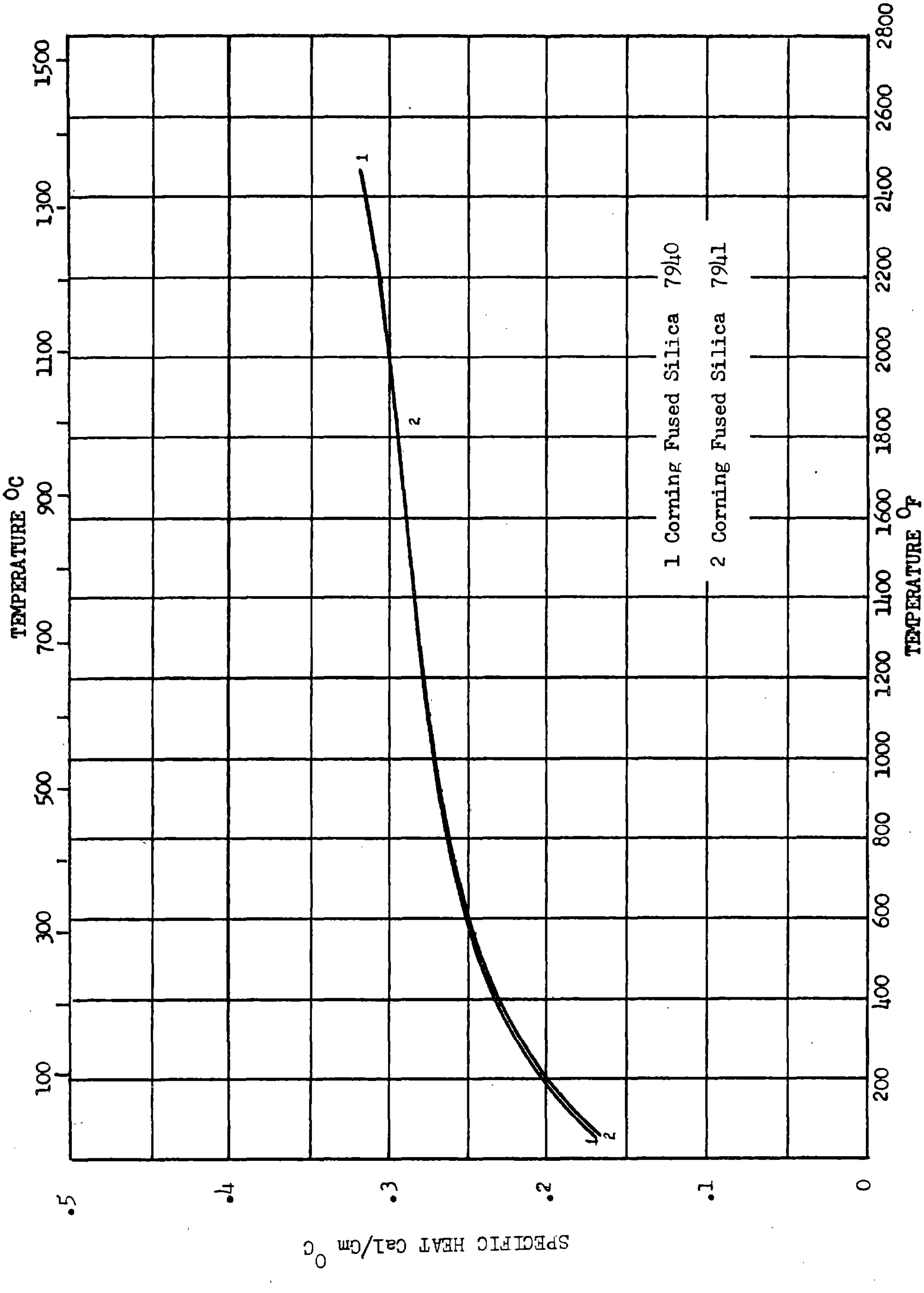


Figure 109

RD 1046

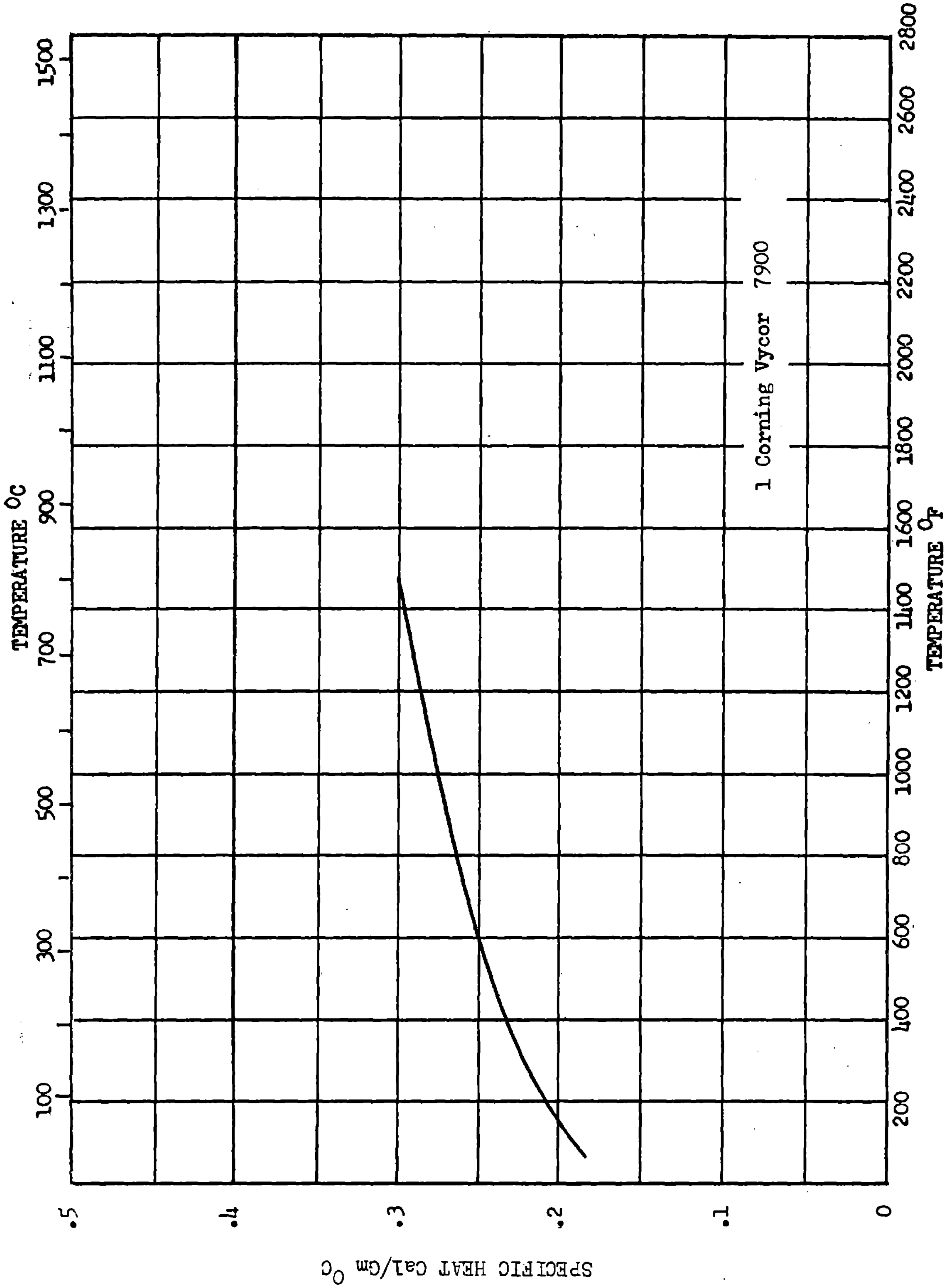


Figure 110

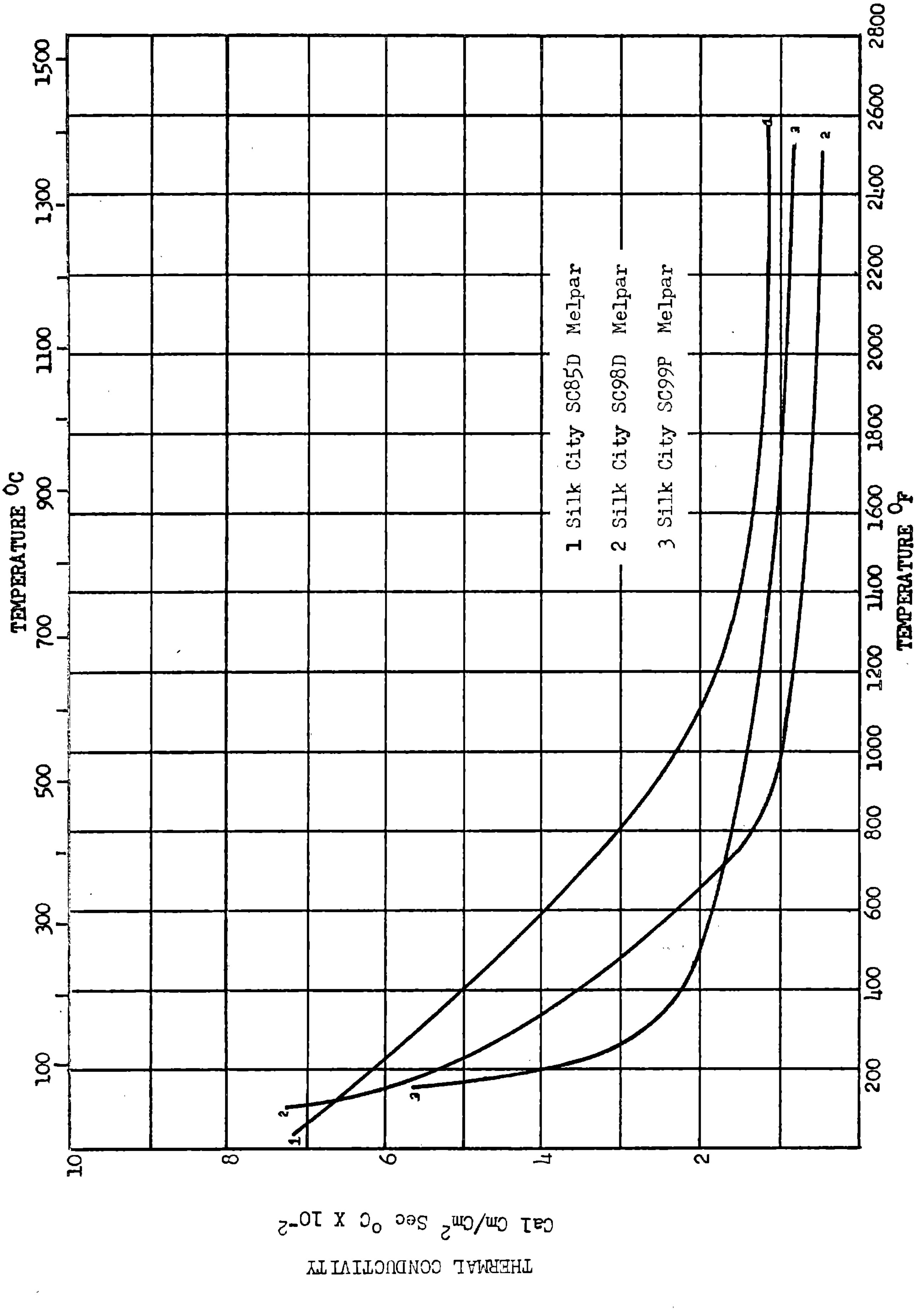

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
1 Silk City SC85D Melpar
2 Silk City SC98D Melpar
3 Silk City SC99P Melpar
1
2
3
10
8
6
4
2
THERMAL CONDUCTIVITY
Cal Cm/Cm² Sec °C X 10⁻²
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 111

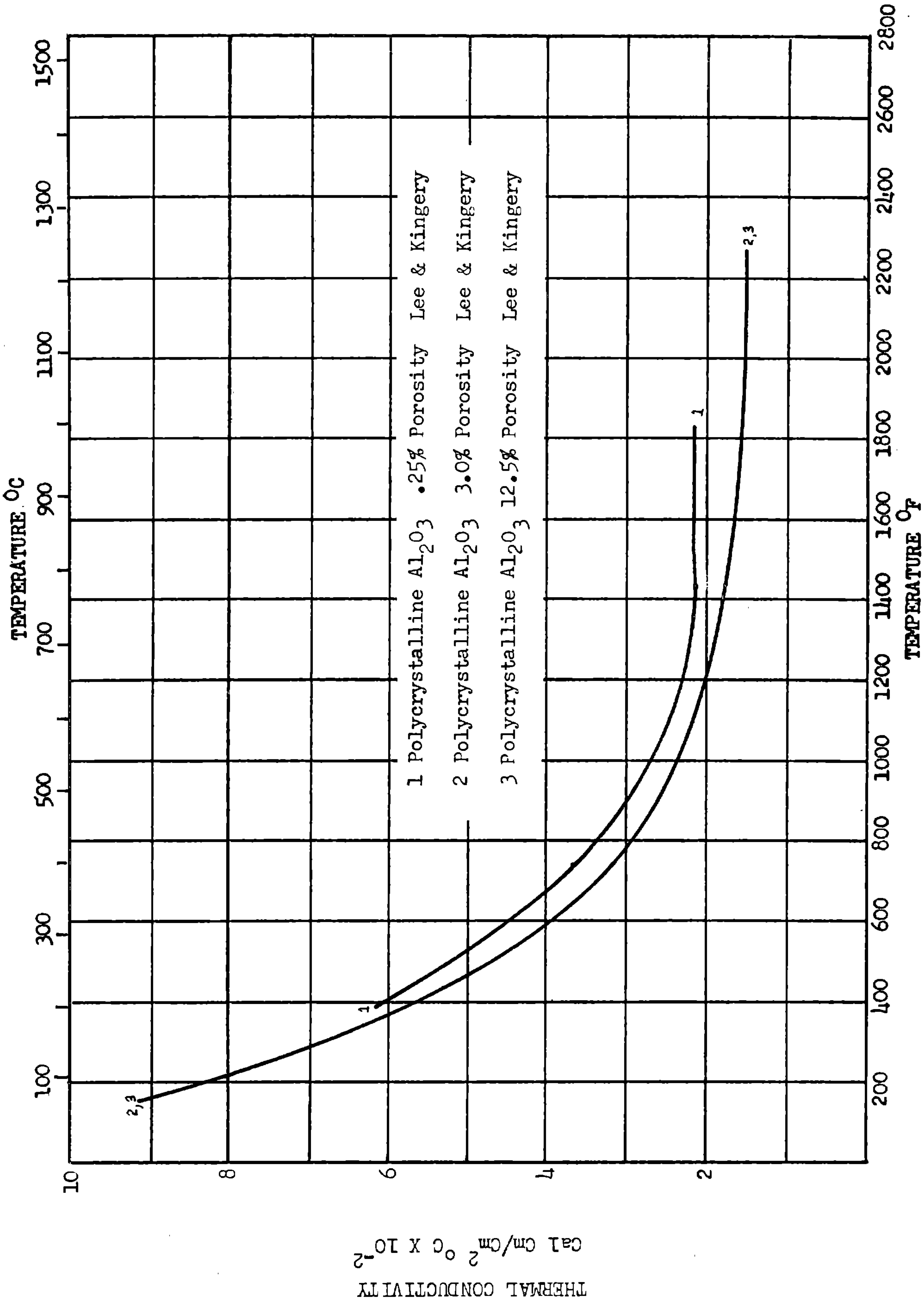

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
TEMPERATURE °F
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
10
8
6
4
2
THERMAL CONDUCTIVITY
Cal Cm/Cm² °C X 10⁻²
1 Polycrystalline Al_2O_3 .25% Porosity Lee & Kingery
2 Polycrystalline Al_2O_3 3.0% Porosity Lee & Kingery
3 Polycrystalline Al_2O_3 12.5% Porosity Lee & Kingery
1
2,3

Figure 112

RD 1046

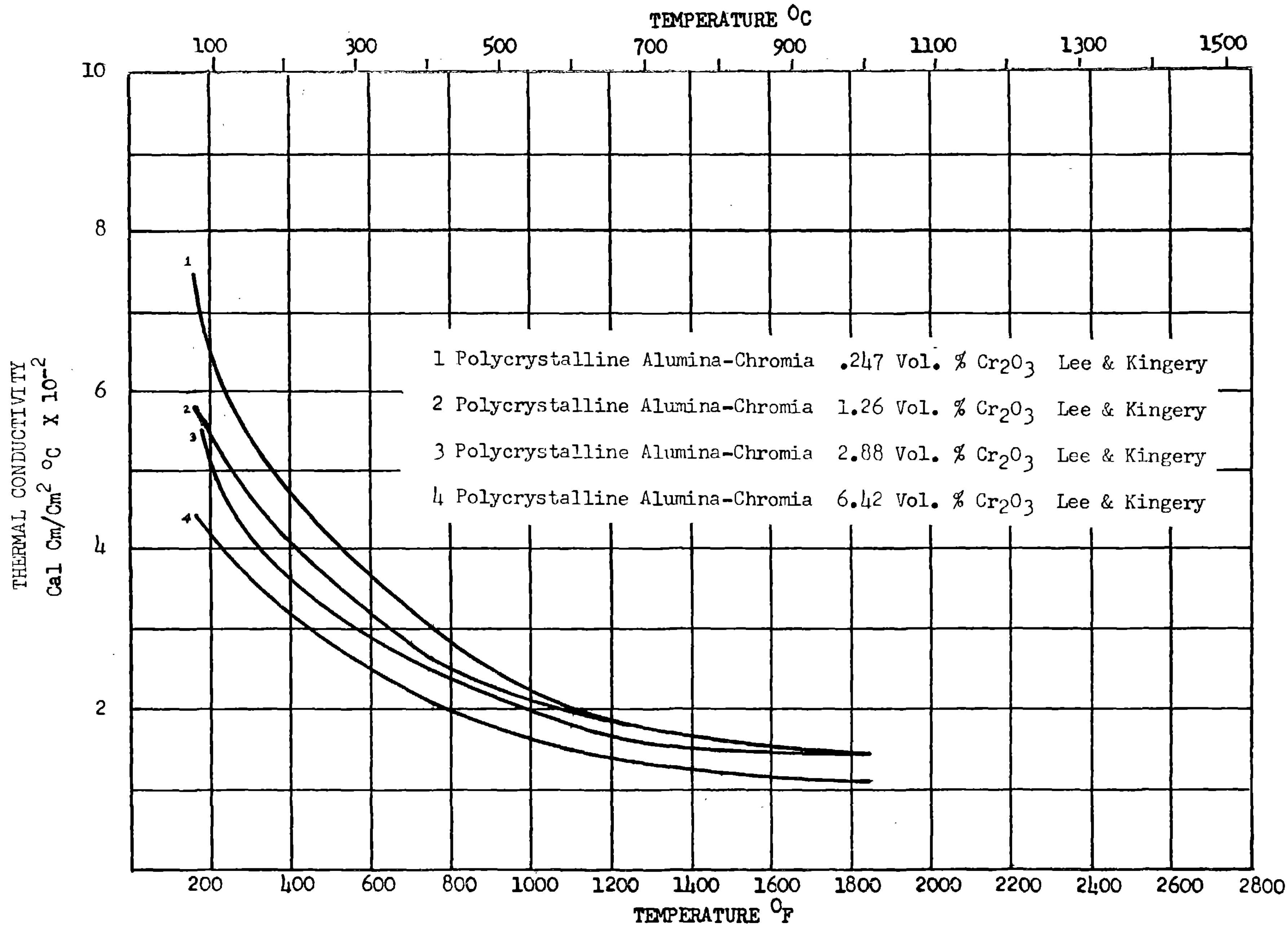


Figure 113

RD 1046

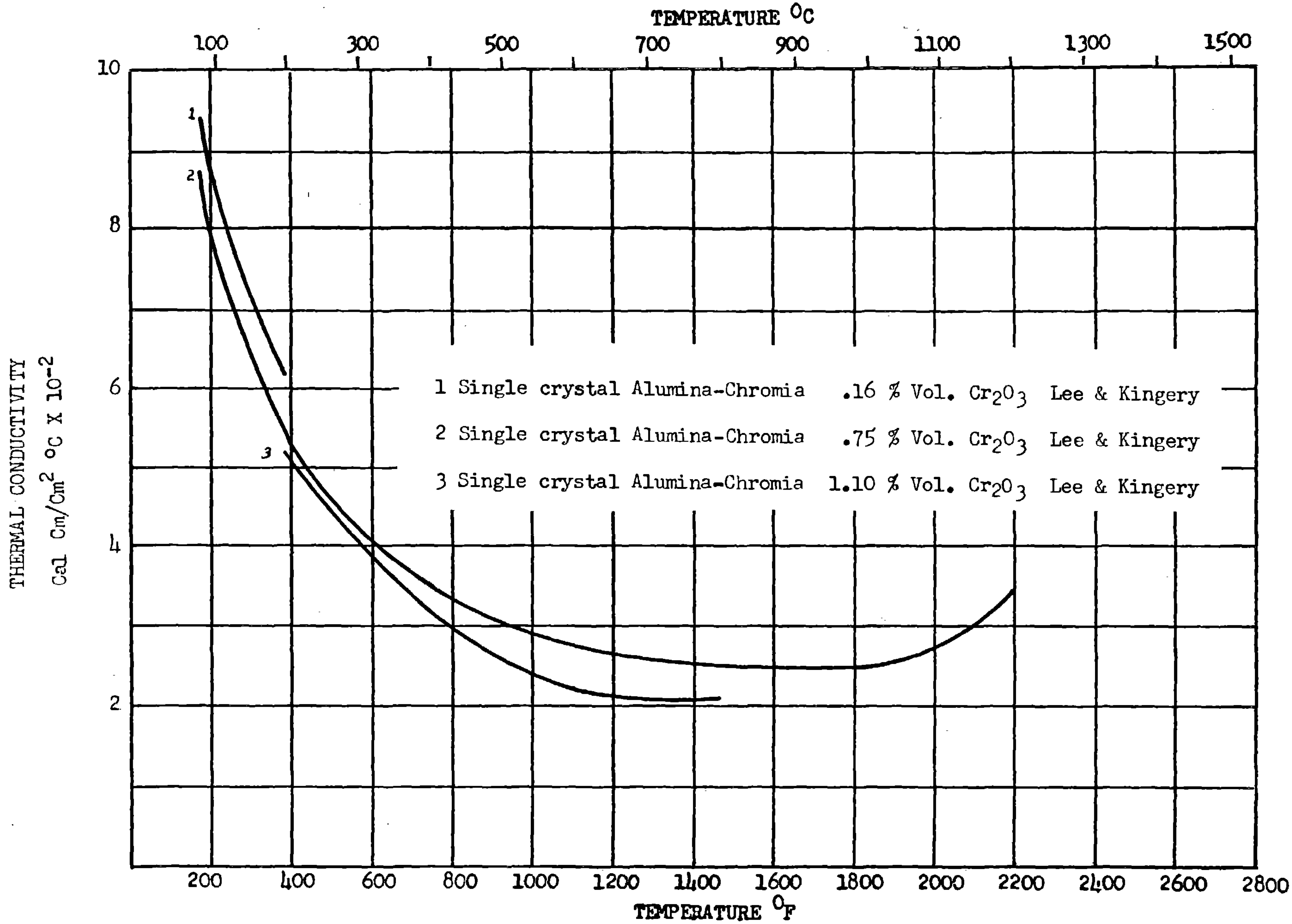


Figure 114

RD 1046

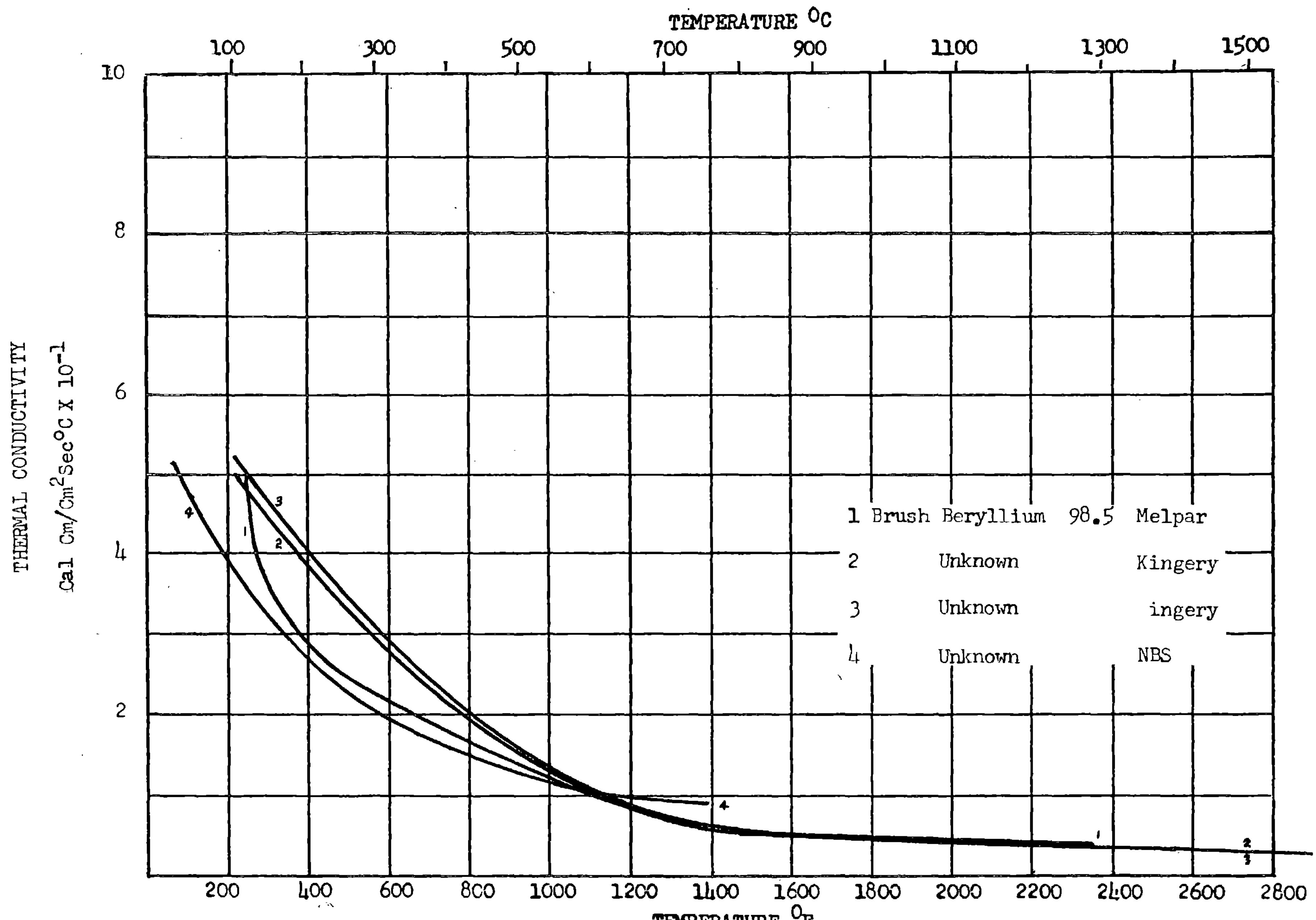


Figure 115

RD 1046

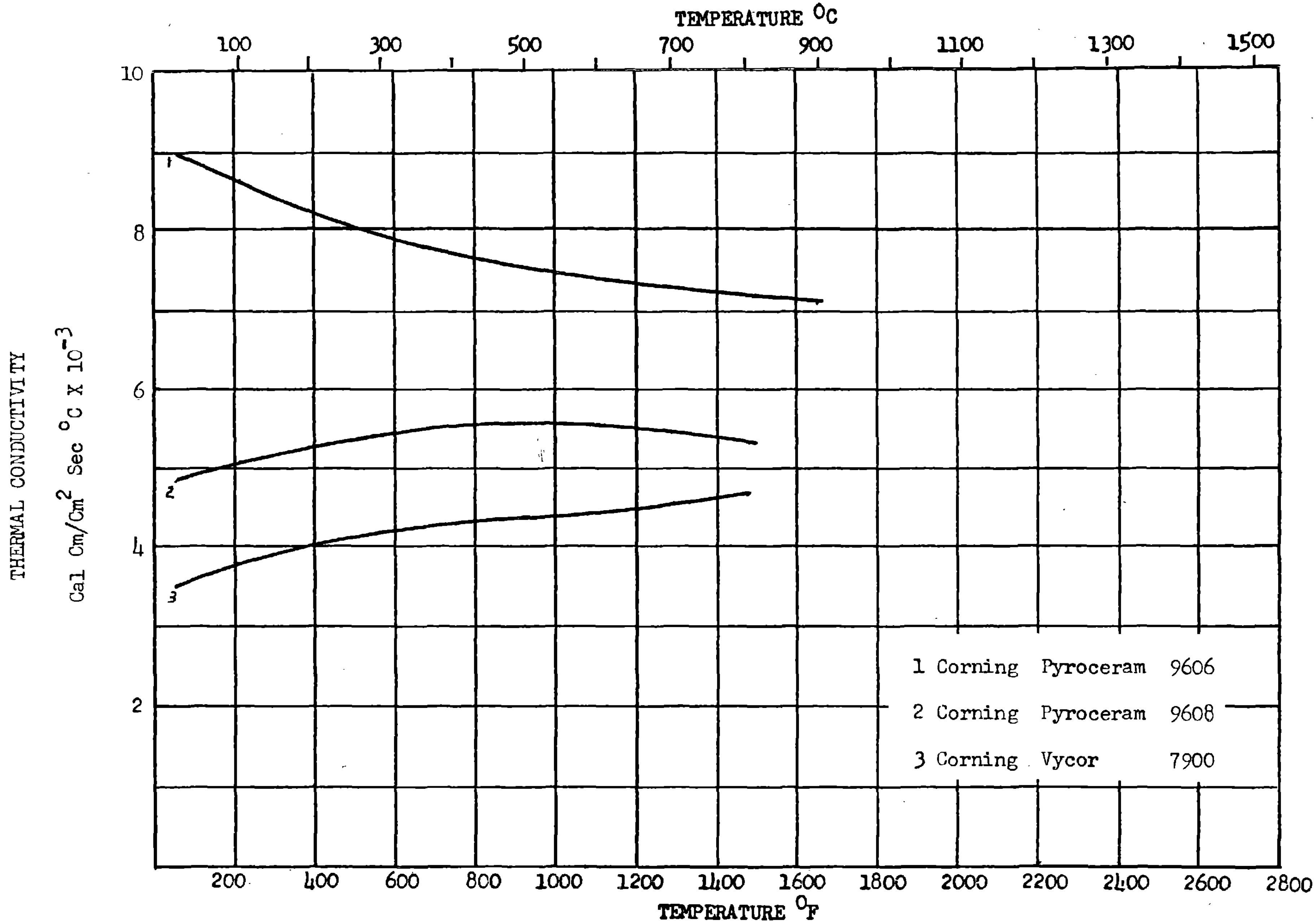


Figure 116

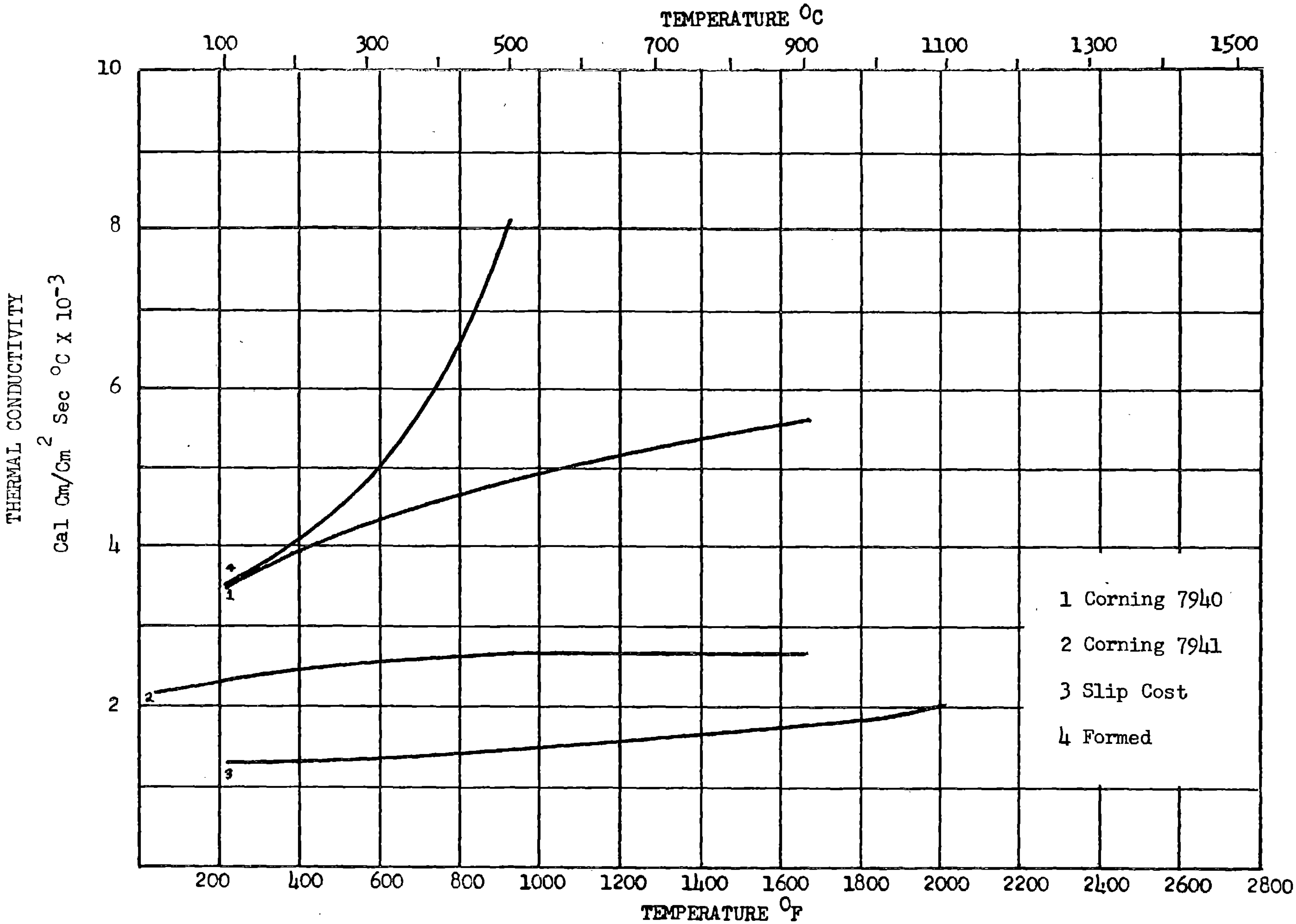

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
THERMAL CONDUCTIVITY
Cal Cm/Cm² Sec °C X 10⁻³
10
8
6
4
2
1 Corning 7940
2 Corning 7941
3 Slip Cost
4 Formed
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 117

RD 1046

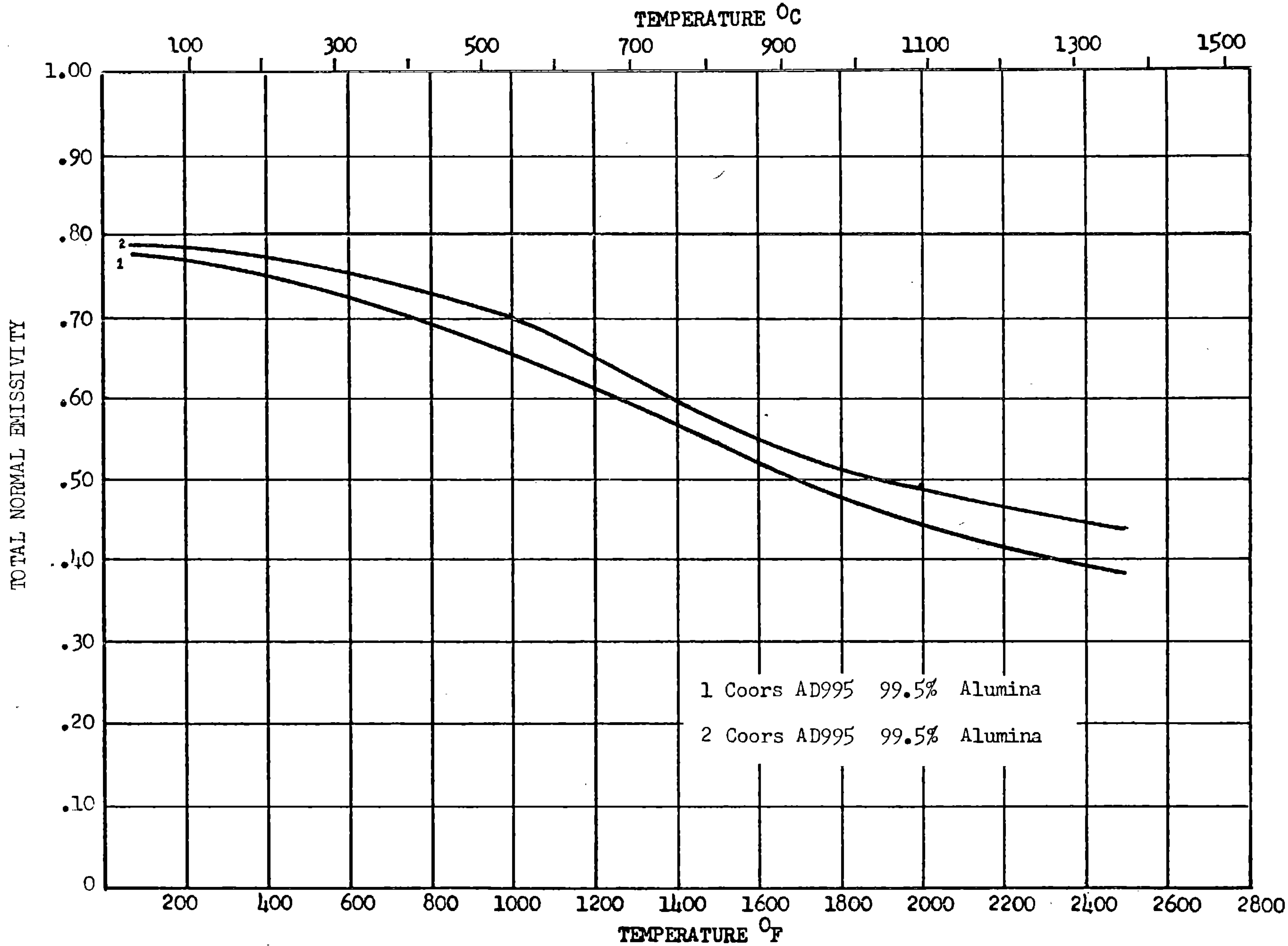


Figure 118

RD 1046

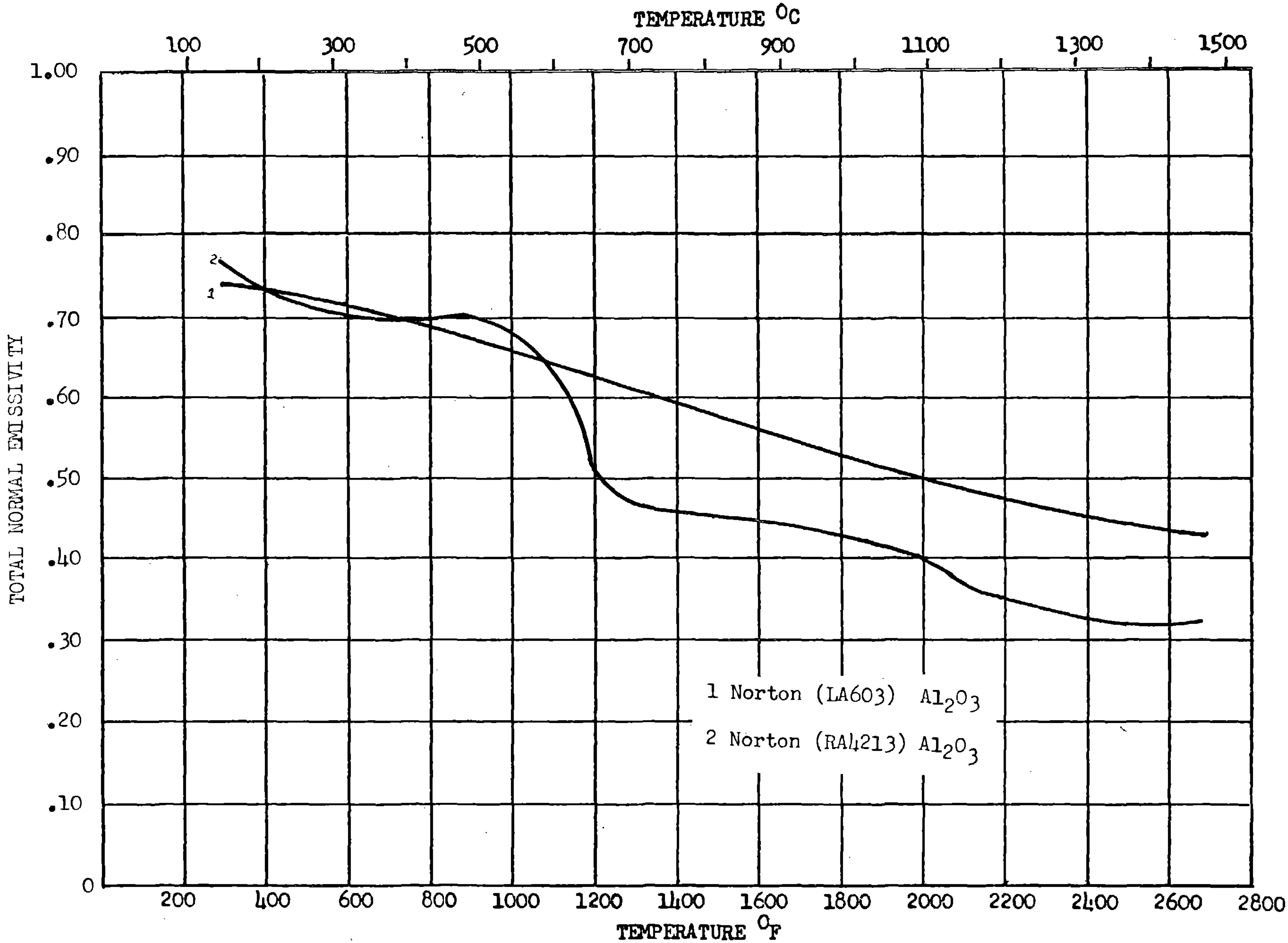


Figure 119

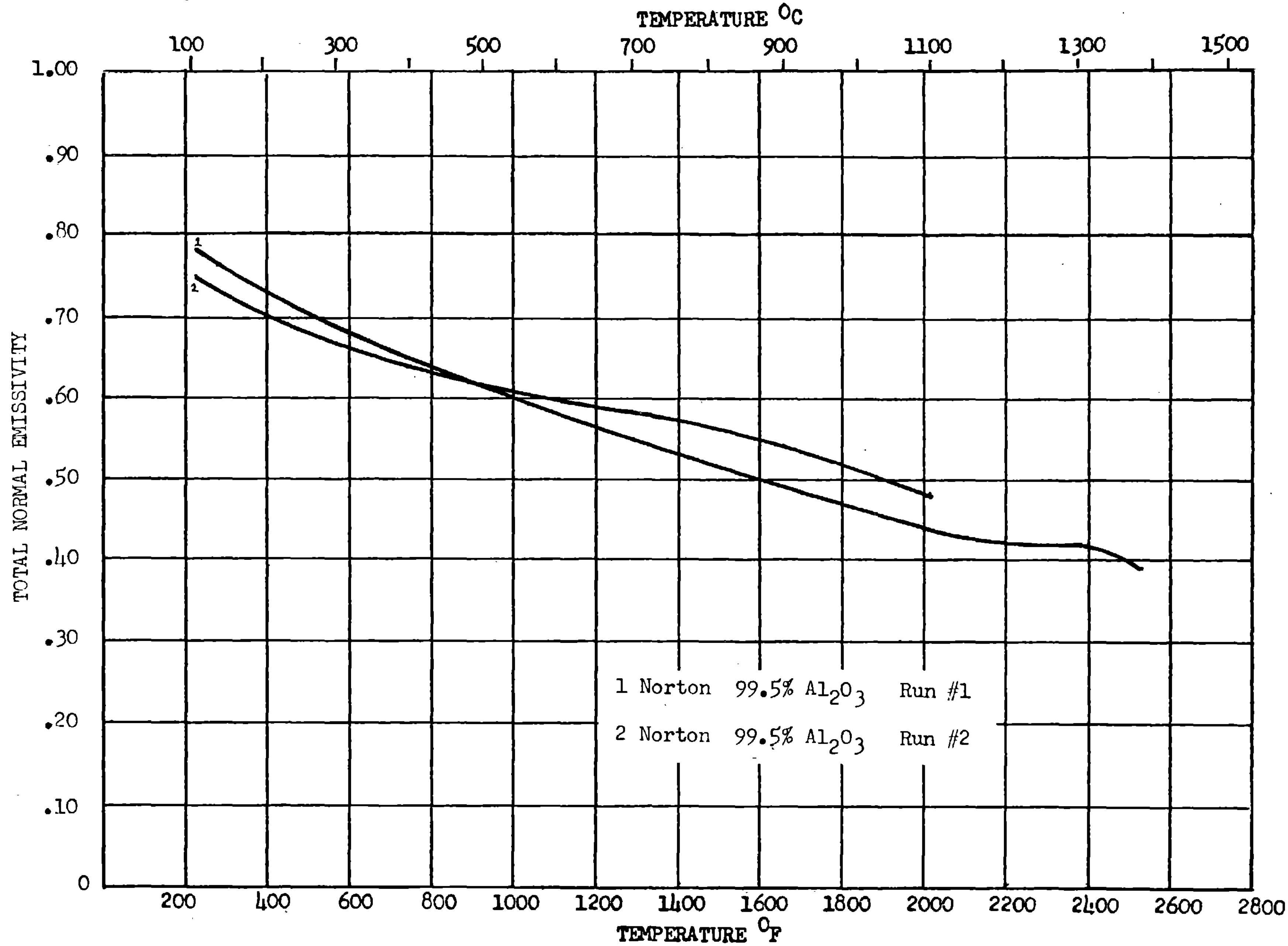

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
TOTAL NORMAL EMISSIVITY
1
2
1 Norton 99.5% Al_2O_3 Run #1
2 Norton 99.5% Al_2O_3 Run #2
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 120

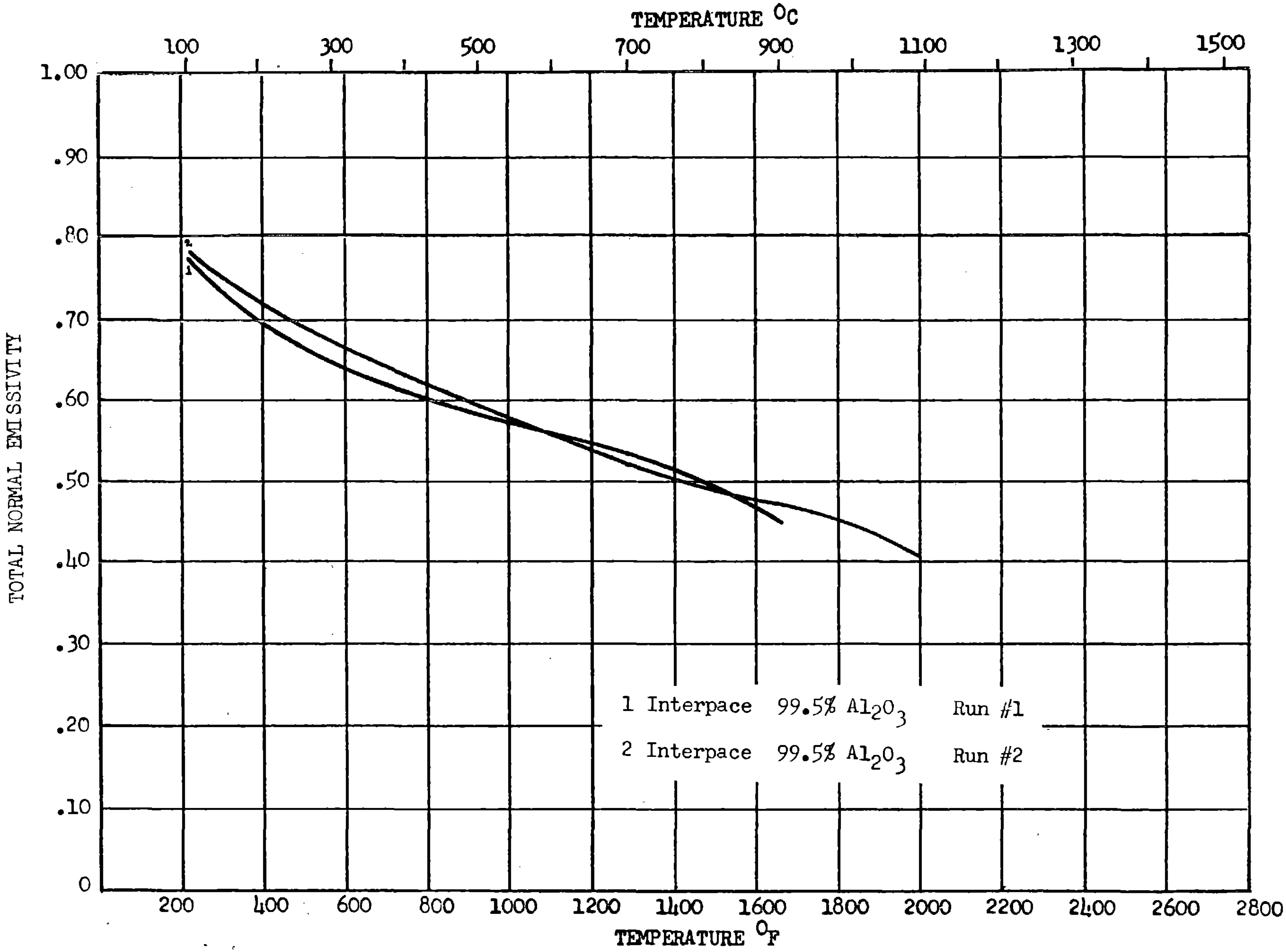

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
TOTAL NORMAL EMISSIVITY
1 Interpace 99.5% Al_2O_3 Run #1
2 Interpace 99.5% Al_2O_3 Run #2
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 121

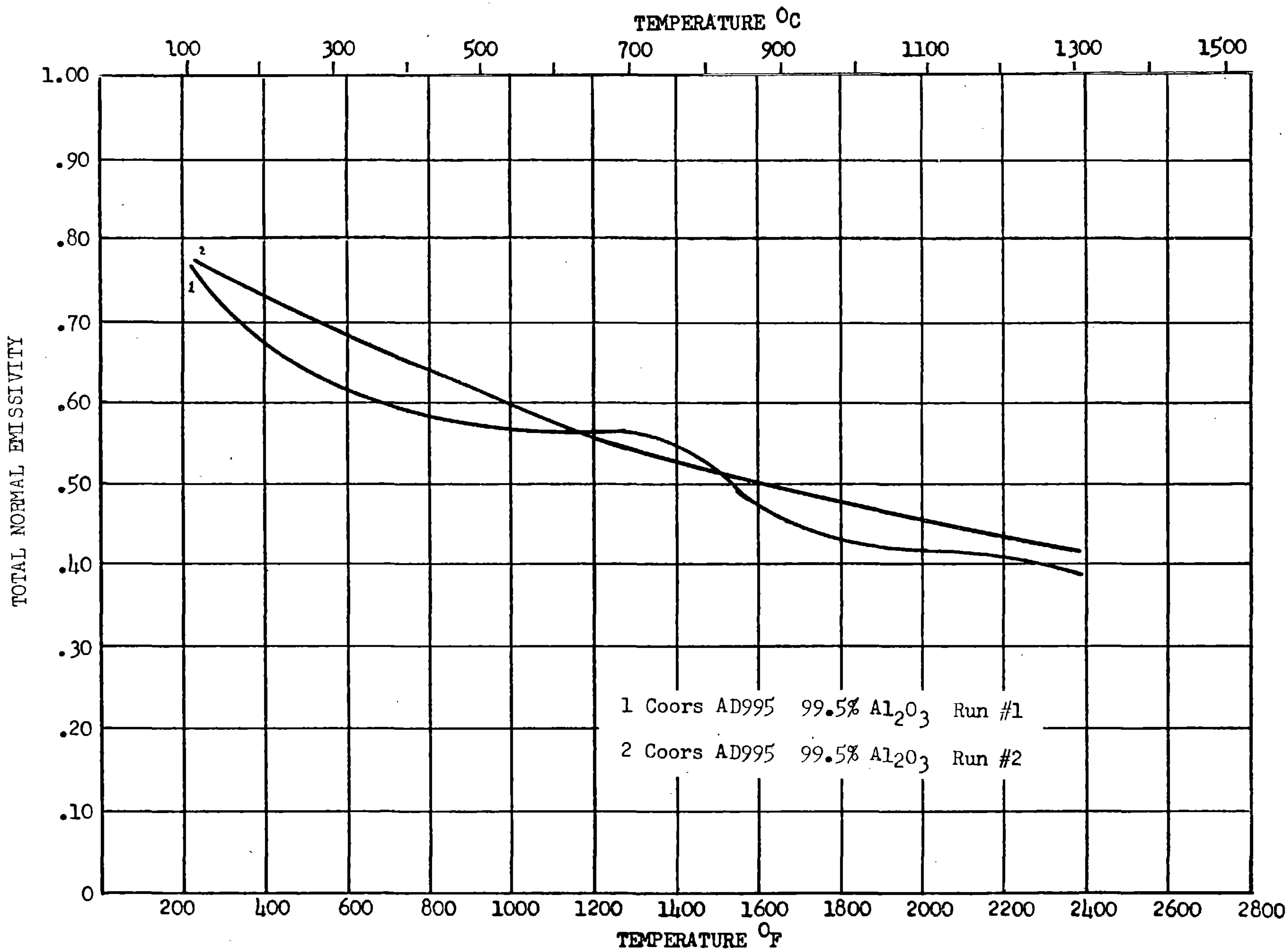

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
TOTAL NORMAL EMISSIVITY
2
1
1 Coors AD995 99.5% Al_2O_3 Run #1
2 Coors AD995 99.5% Al_2O_3 Run #2
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 122

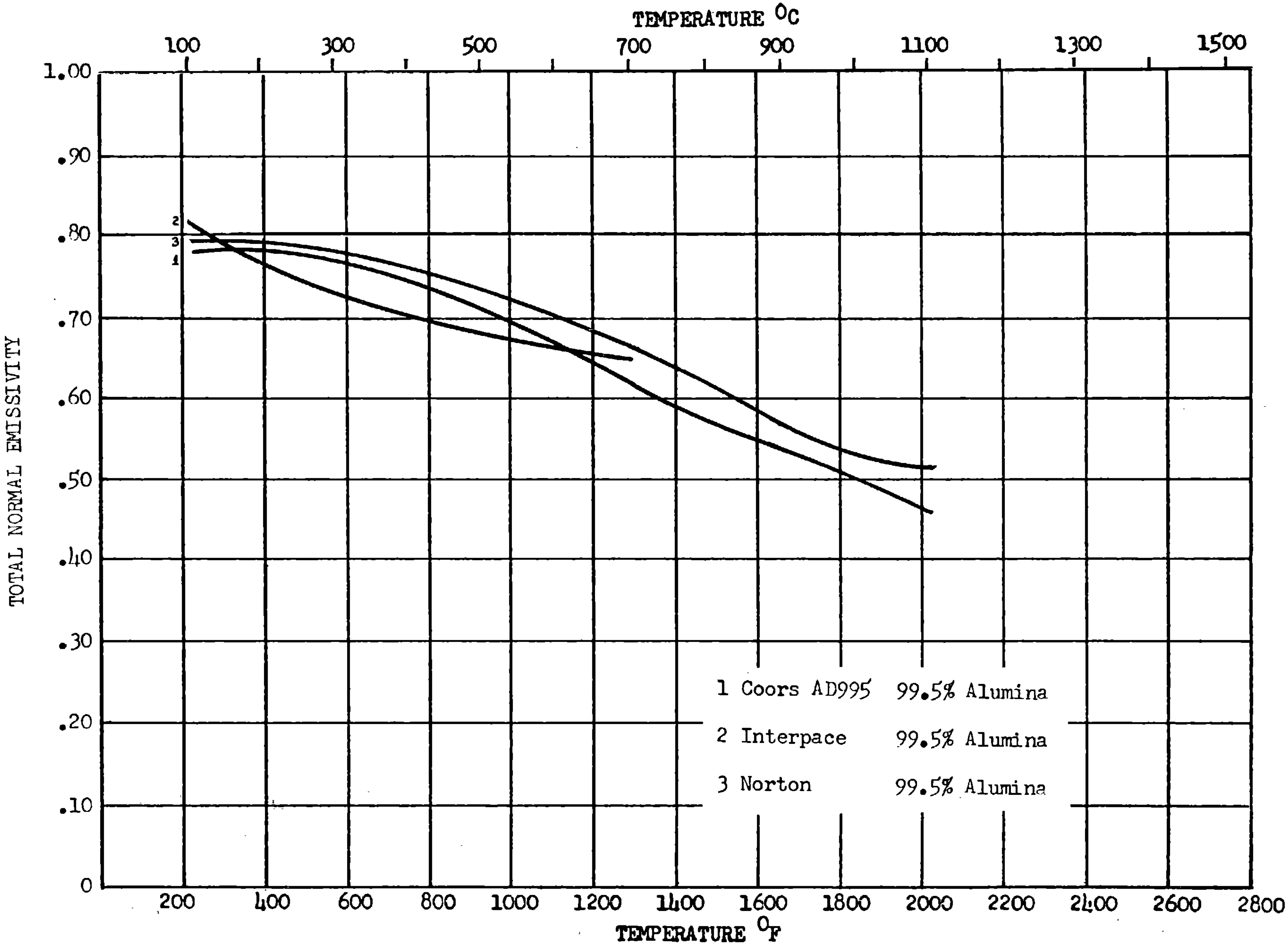

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
TOTAL NORMAL EMISSIVITY
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
2
3
1
1 Coors AD995 99.5% Alumina
2 Interpace 99.5% Alumina
3 Norton 99.5% Alumina
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 123

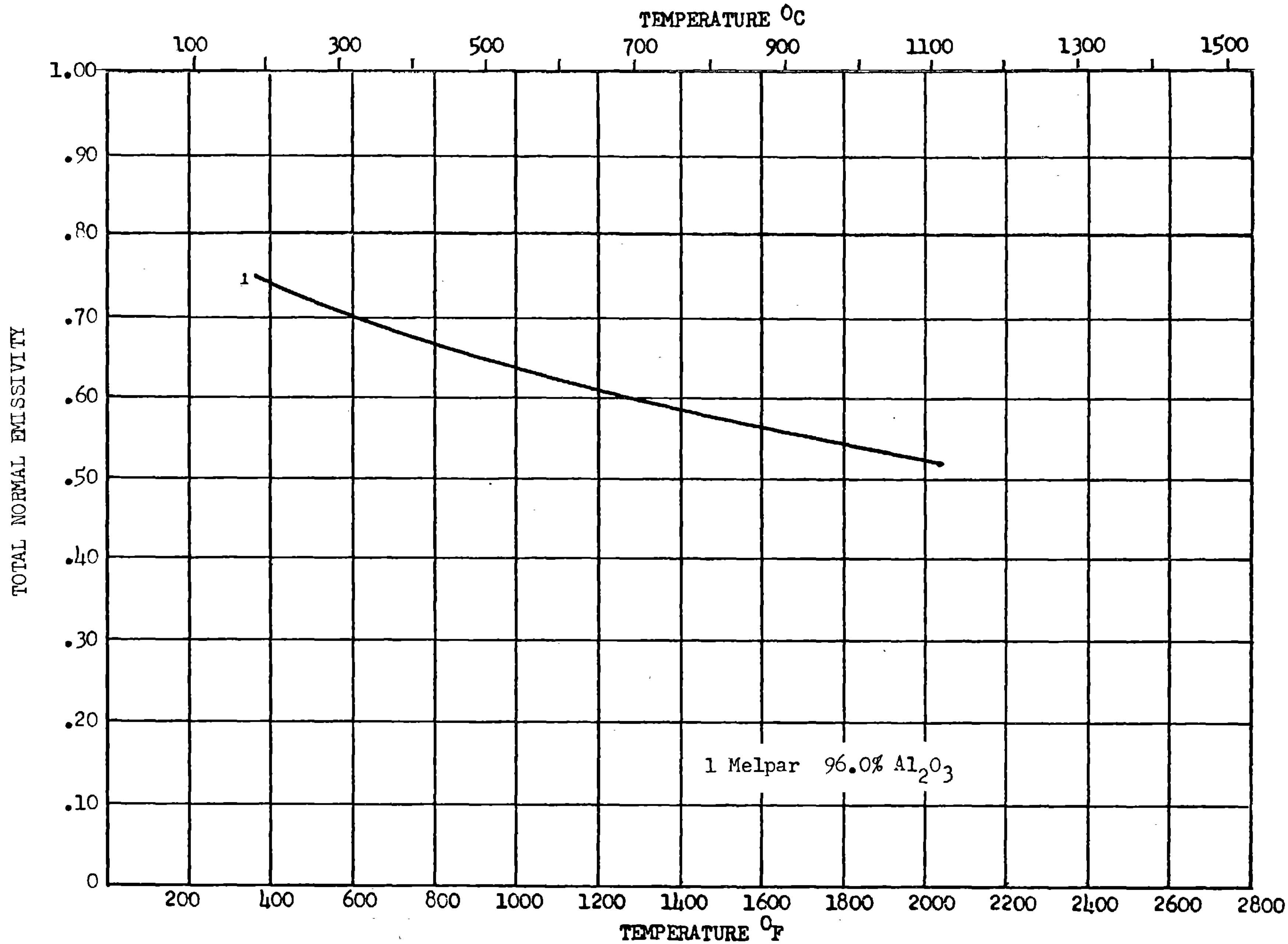

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
TOTAL NORMAL EMISSIVITY
1
1 Melpar 96.0% Al_2O_3
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 124

RD 1046

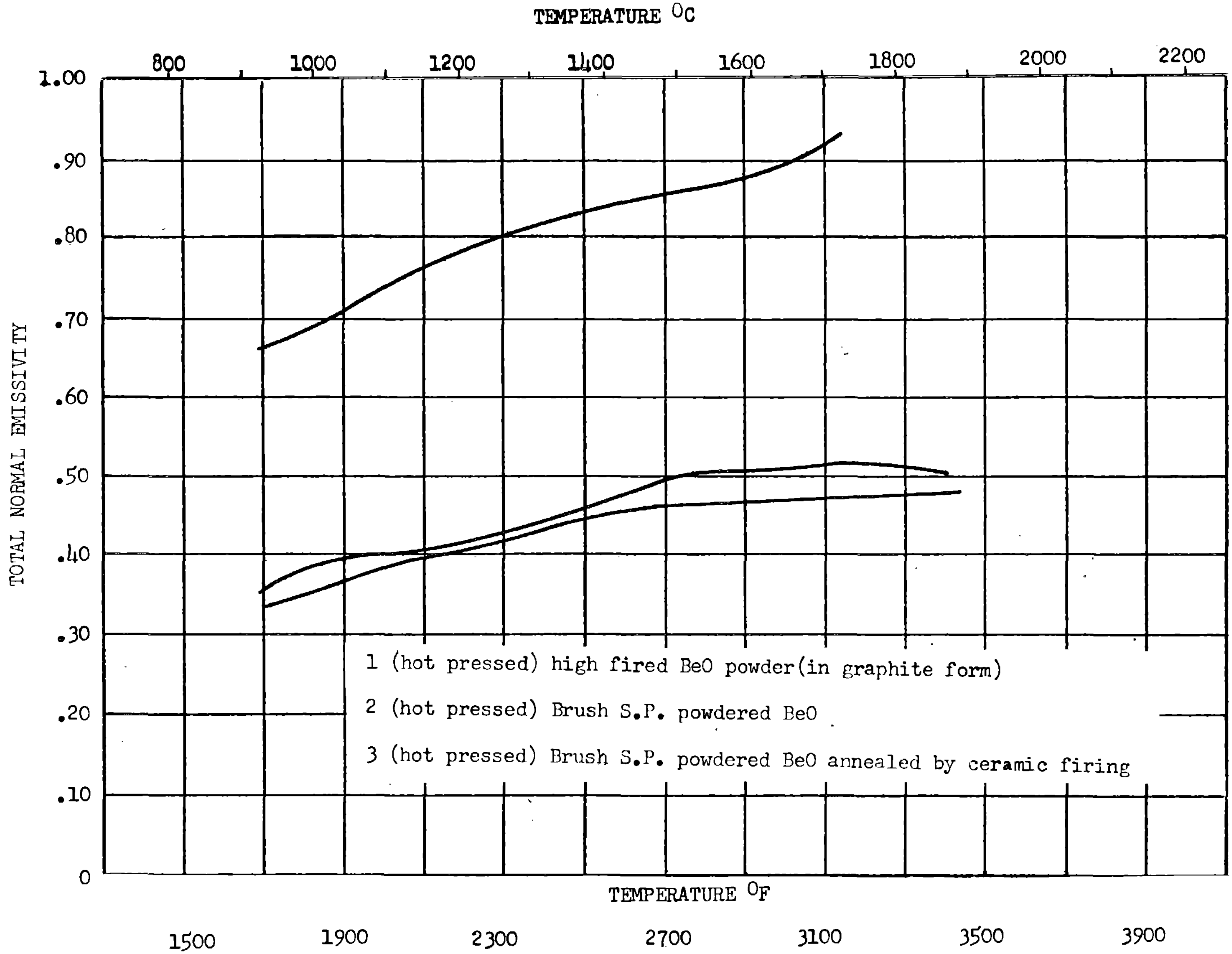


Figure 125

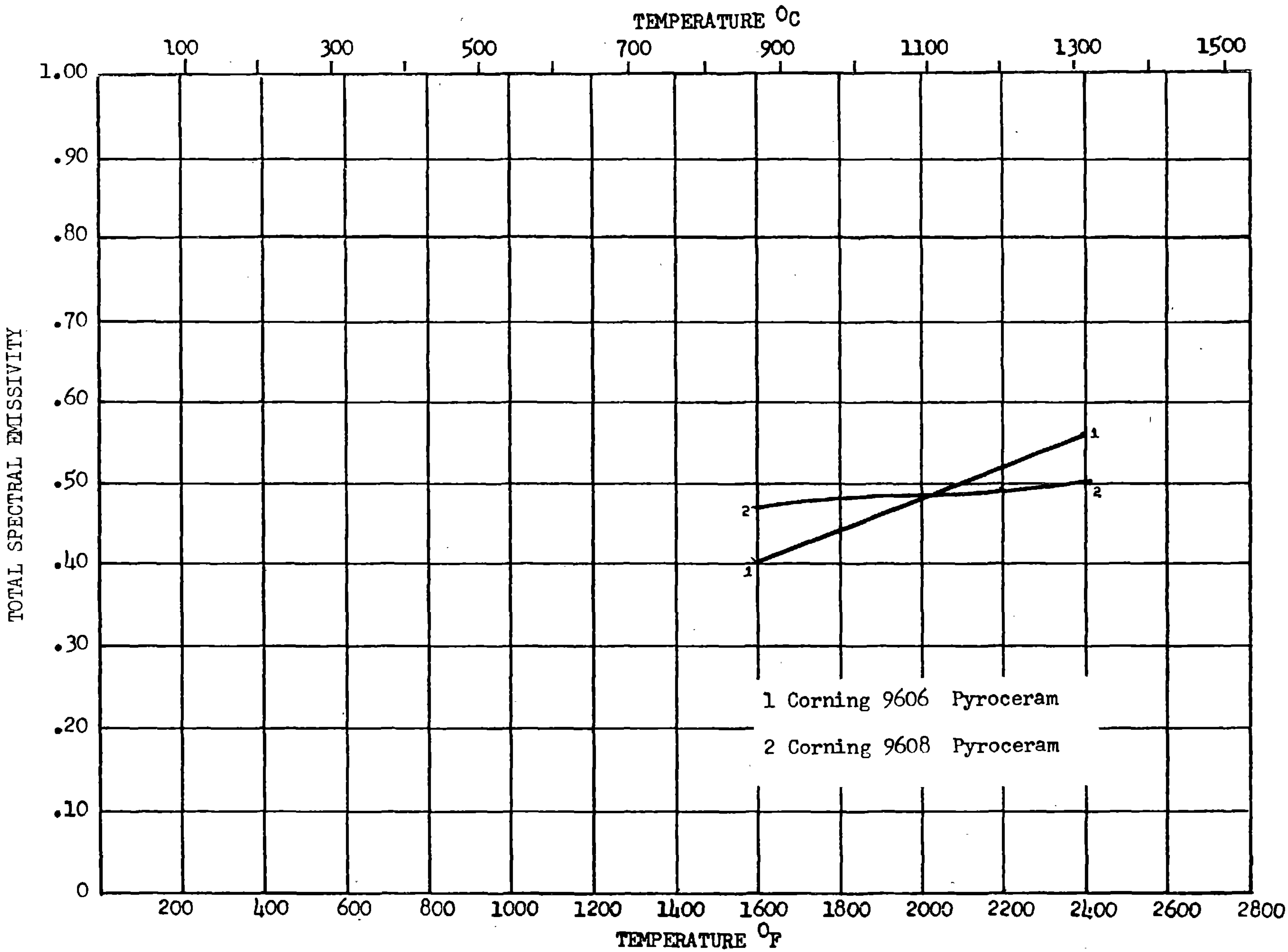

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
TOTAL SPECTRAL EMISSIVITY
1 Corning 9606 Pyroceram
2 Corning 9608 Pyroceram
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 126

RD 1046

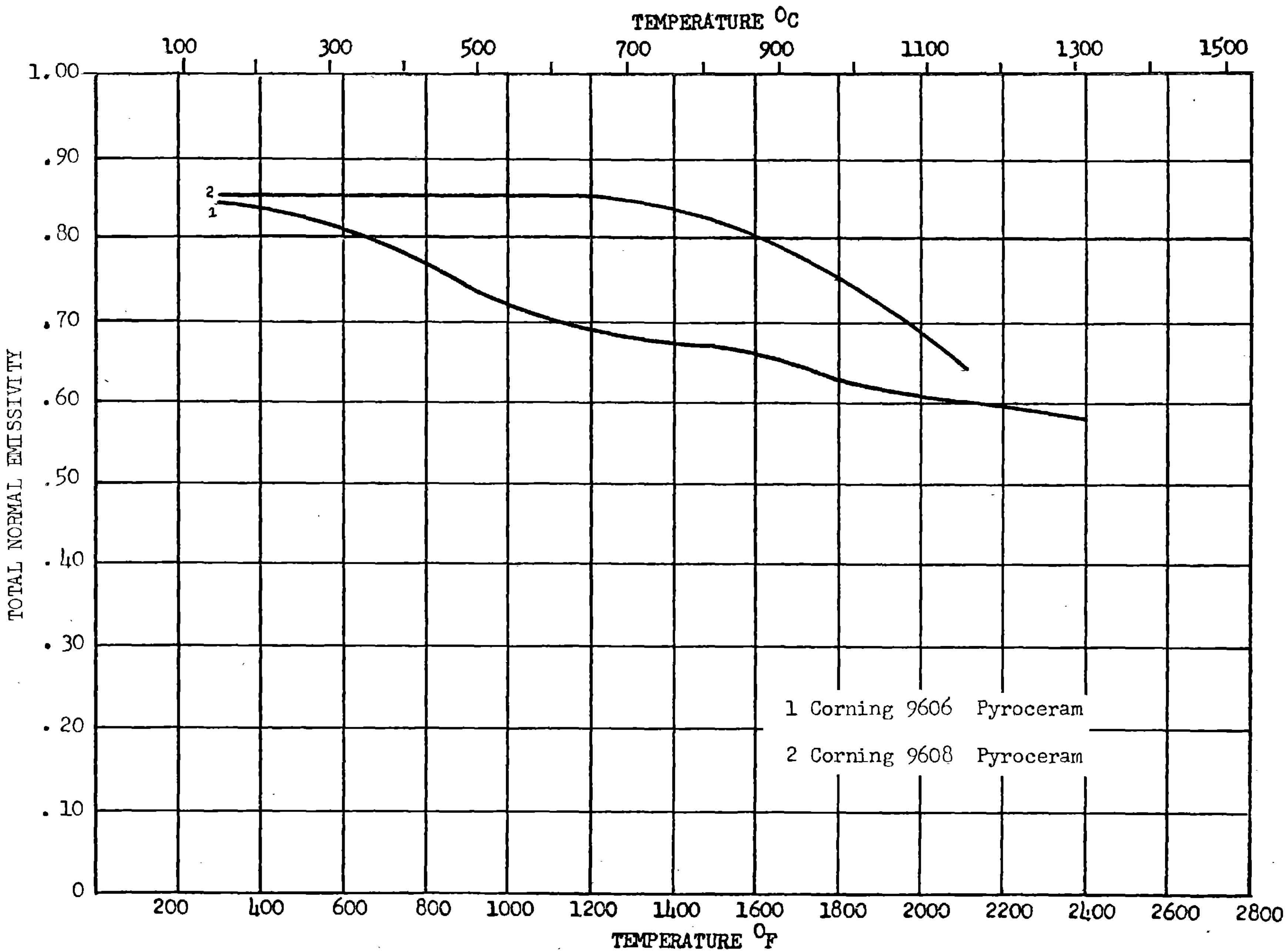


Figure 127

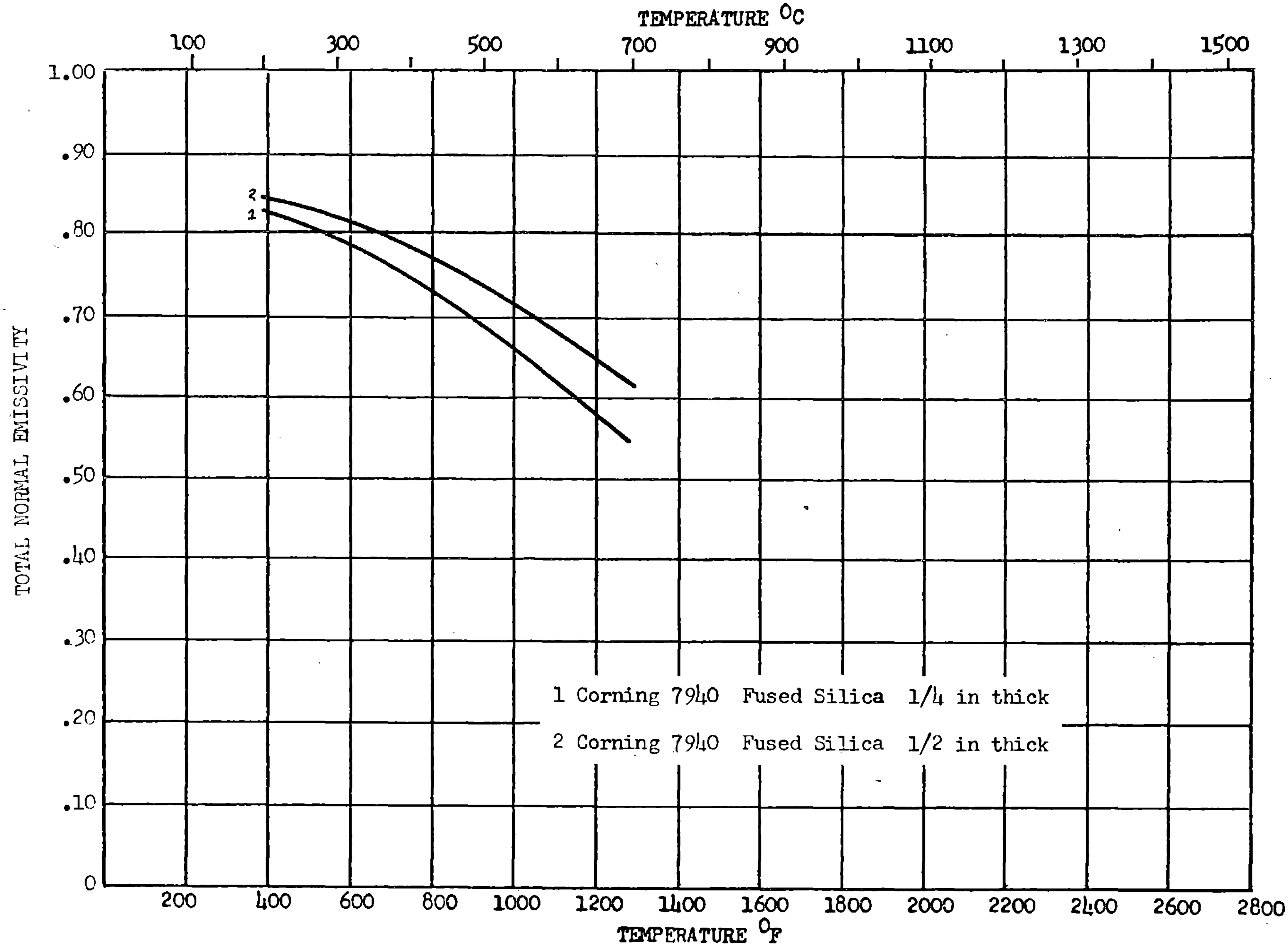

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
TOTAL NORMAL EMISSIVITY
2
1
1 Corning 7940 Fused Silica 1/4 in thick
2 Corning 7940 Fused Silica 1/2 in thick
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 128

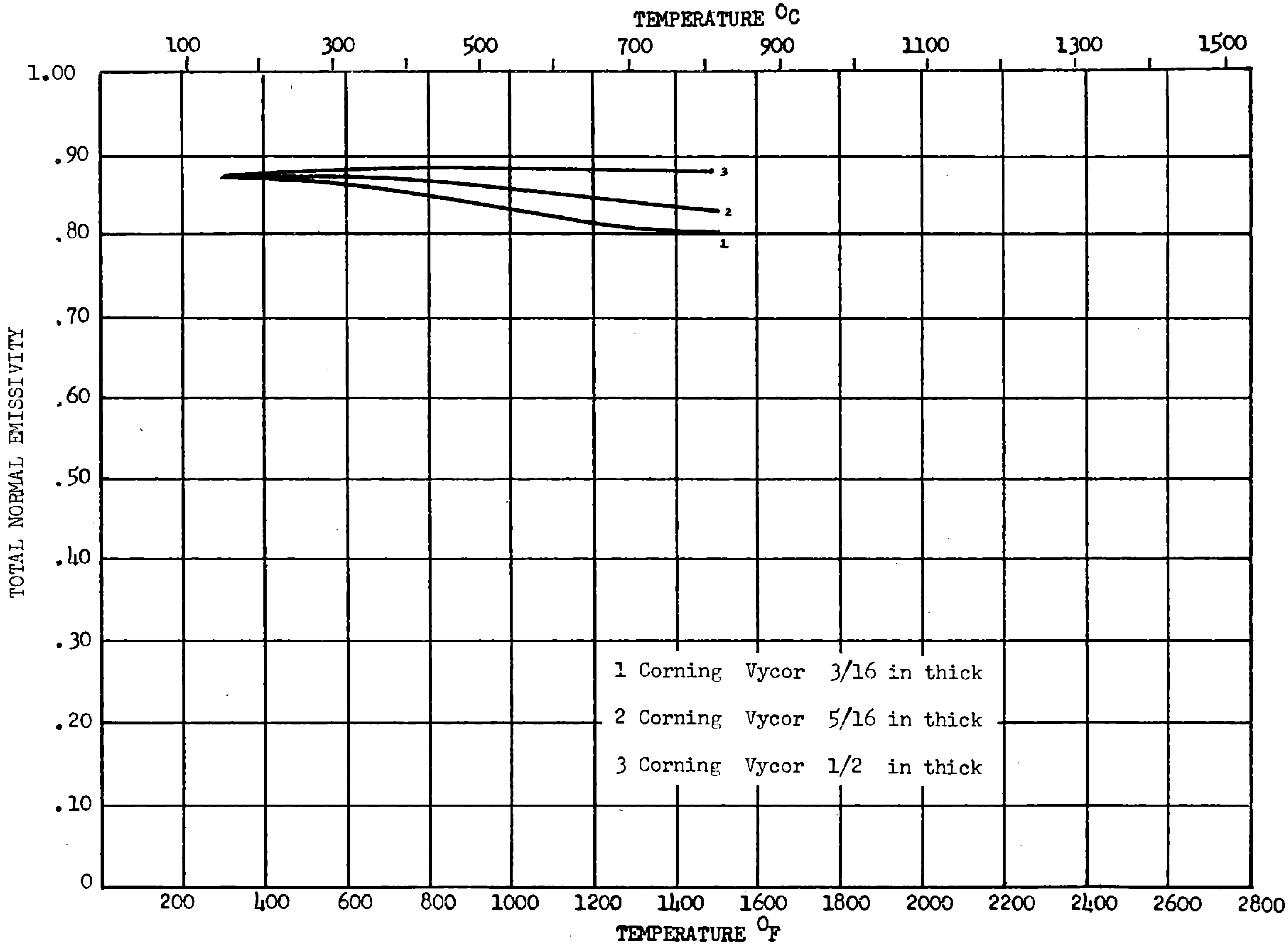

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
TOTAL NORMAL EMISSIVITY
3
2
1
1 Corning Vycor 3/16 in thick
2 Corning Vycor 5/16 in thick
3 Corning Vycor 1/2 in thick
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 129

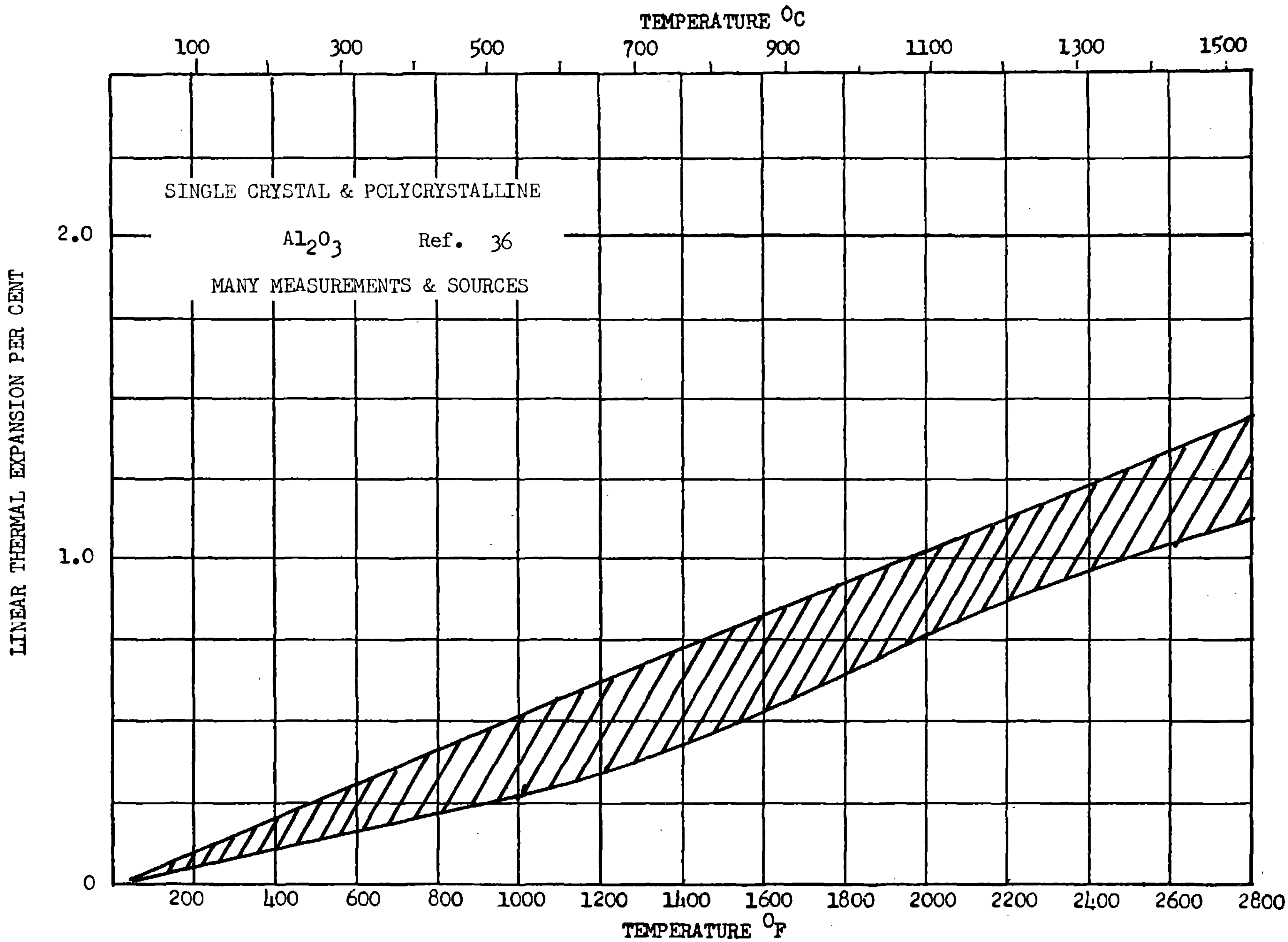

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
SINGLE CRYSTAL & POLYCRYSTALLINE
Al_2O_3 Ref. 36
MANY MEASUREMENTS & SOURCES
LINEAR THERMAL EXPANSION PER CENT
2.0
1.0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 130

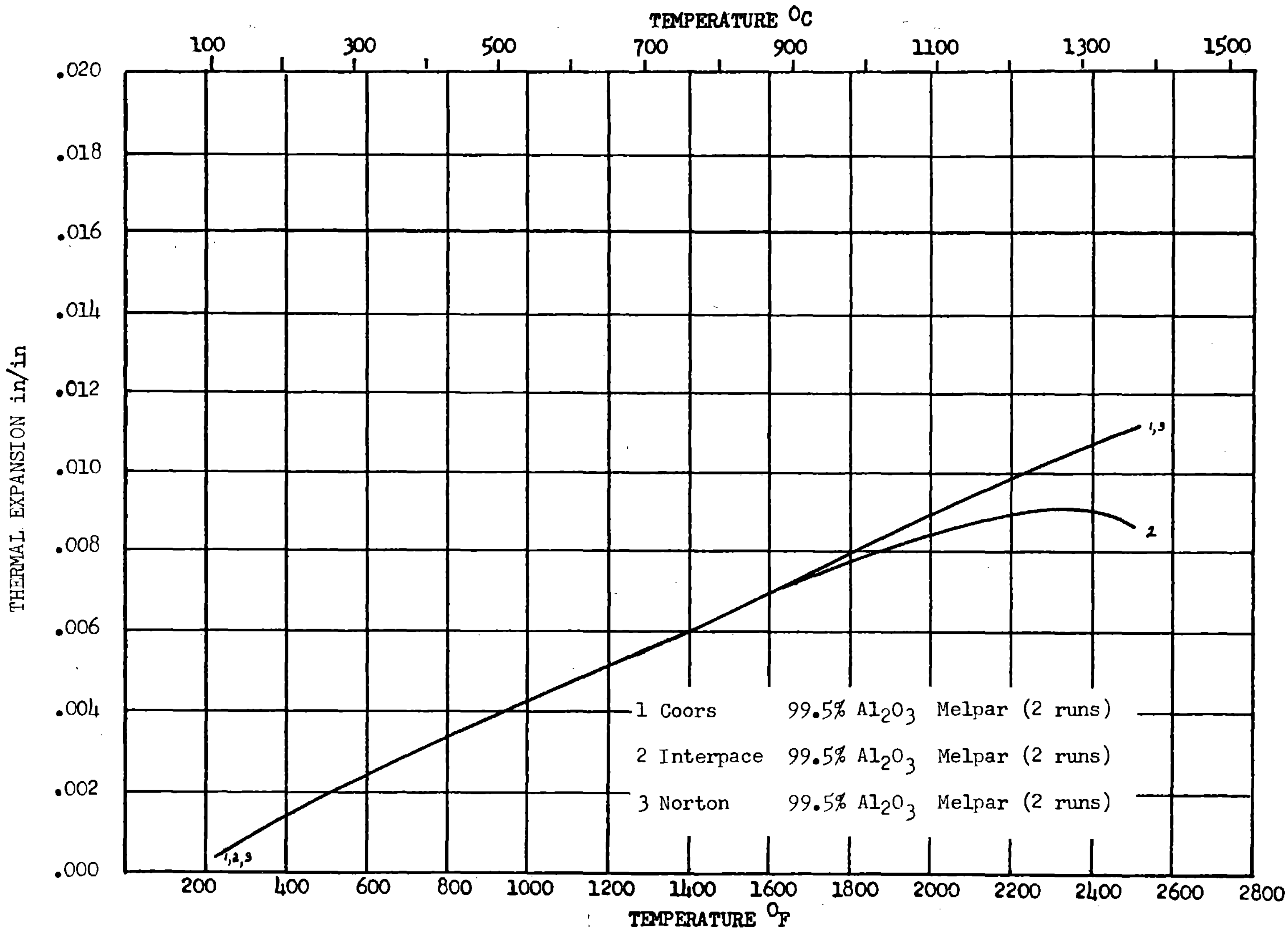

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.020
.018
.016
.014
.012
.010
.008
.006
.004
.002
.000
THERMAL EXPANSION in/in
1,3
2
1,2,3
1 Coors 99.5% Al_2O_3 Melpar (2 runs)
2 Interpace 99.5% Al_2O_3 Melpar (2 runs)
3 Norton 99.5% Al_2O_3 Melpar (2 runs)
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 131

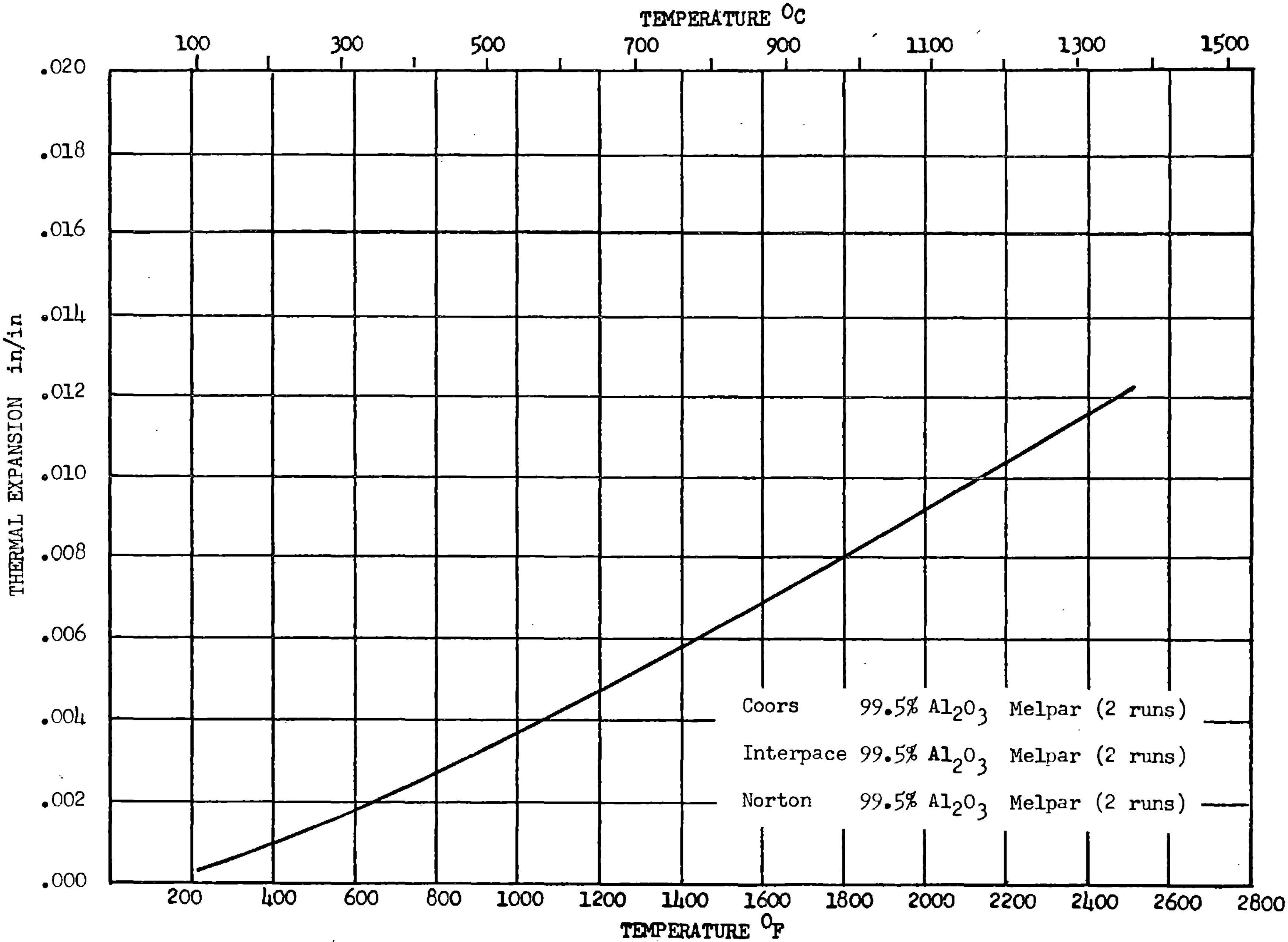

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
THERMAL EXPANSION in/in
.020
.018
.016
.014
.012
.010
.008
.006
.004
.002
.000
Coors 99.5% Al2O3 Melpar (2 runs)
Interpace 99.5% Al2O3 Melpar (2 runs)
Norton 99.5% Al2O3 Melpar (2 runs)
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 132

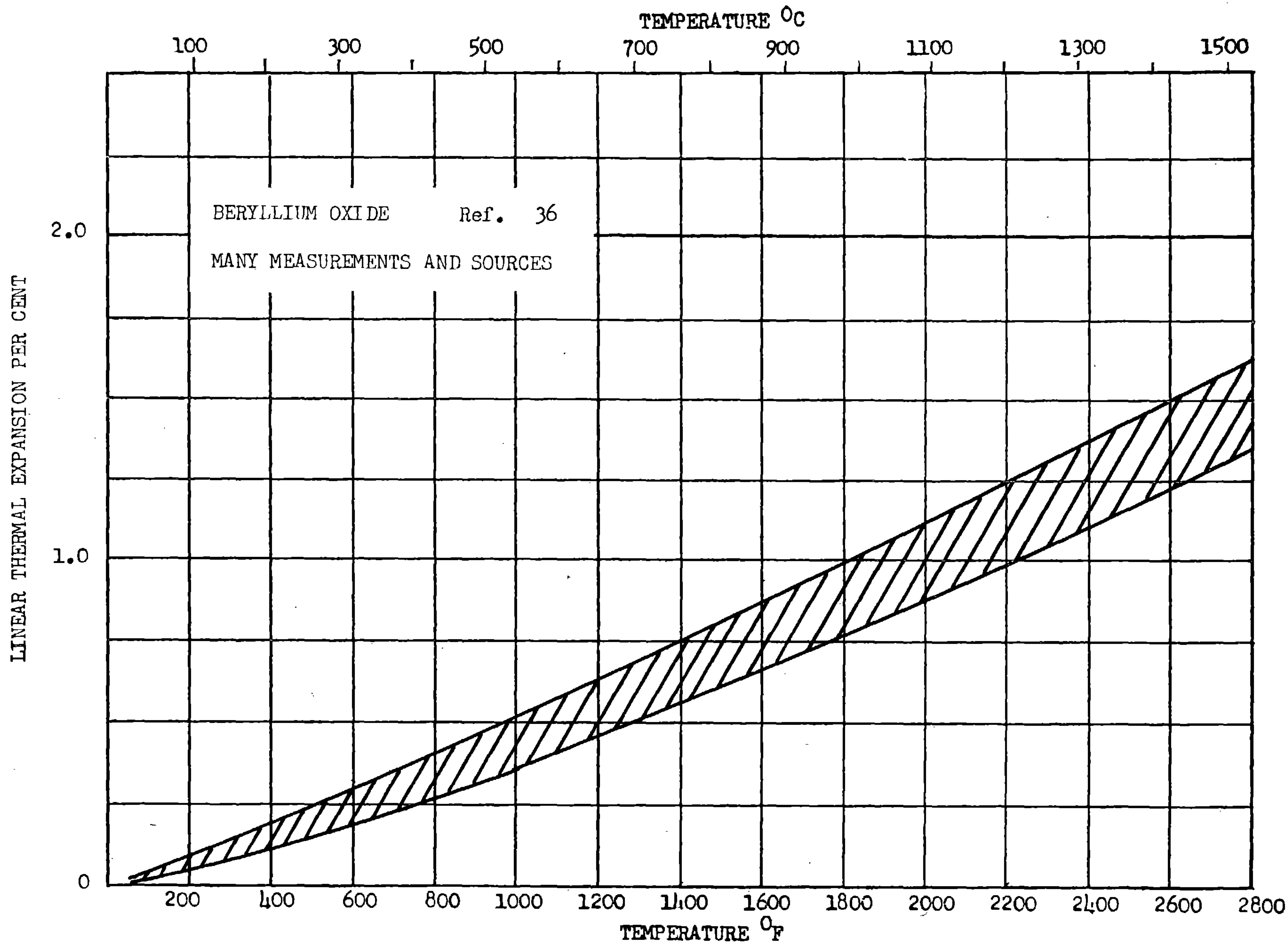

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
BERYLLIUM OXIDE Ref. 36
MANY MEASUREMENTS AND SOURCES
LINEAR THERMAL EXPANSION PER CENT
2.0
1.0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 133

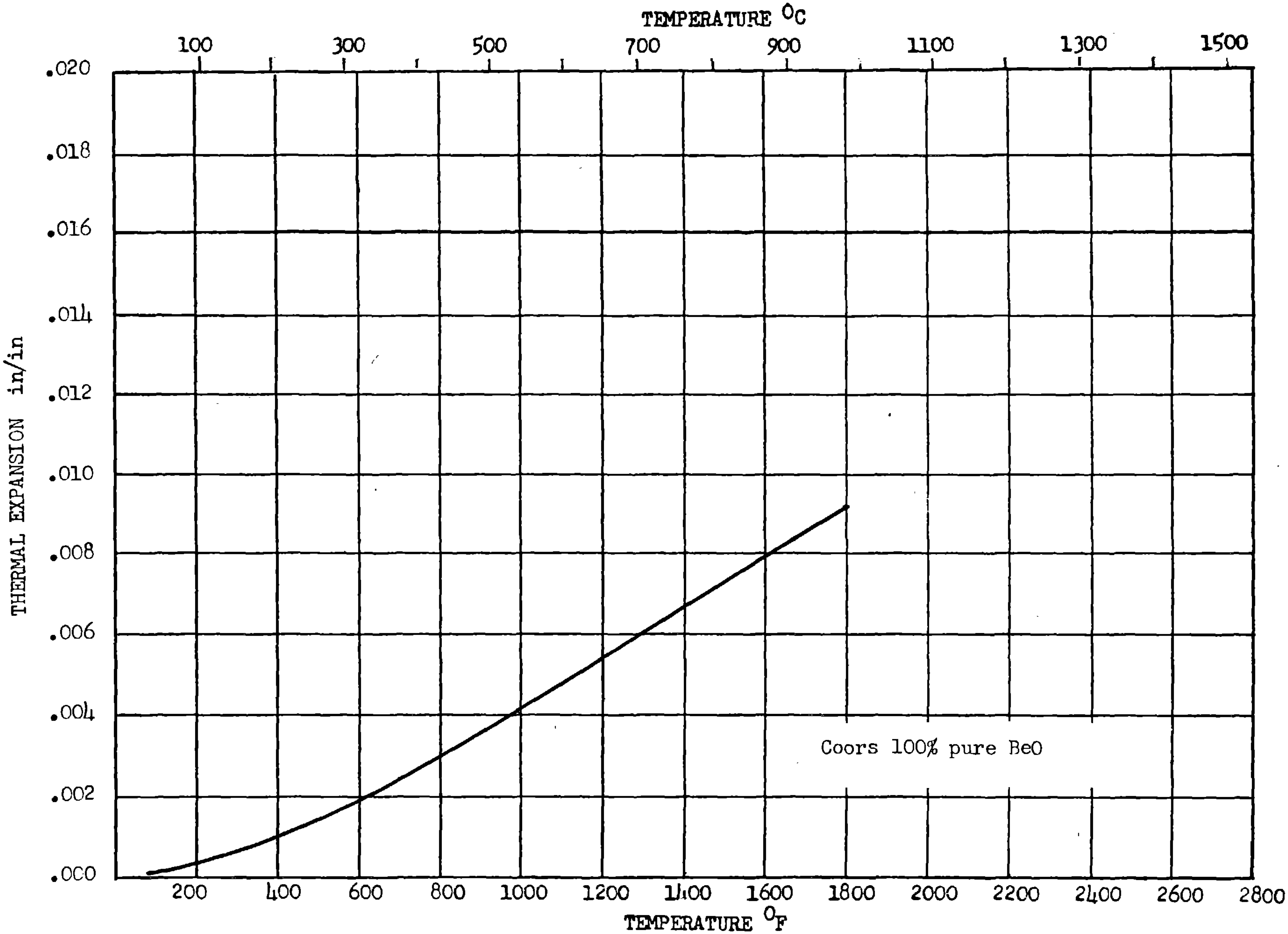

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
.020
.018
.016
.014
.012
.010
.008
.006
.004
.002
.000
THERMAL EXPANSION in/in
Coors 100% pure BeO
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 134

RD 1046

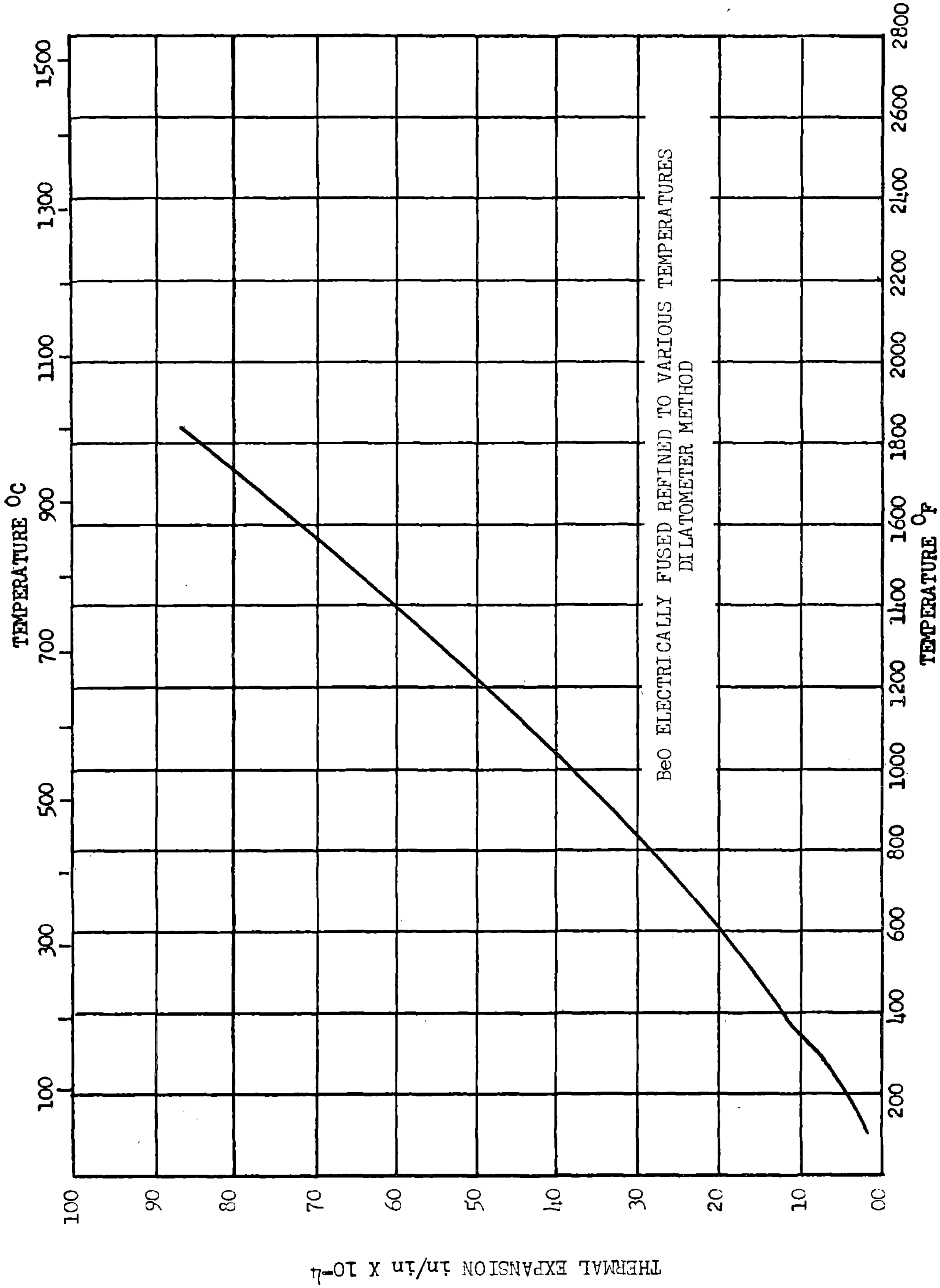


Figure 135

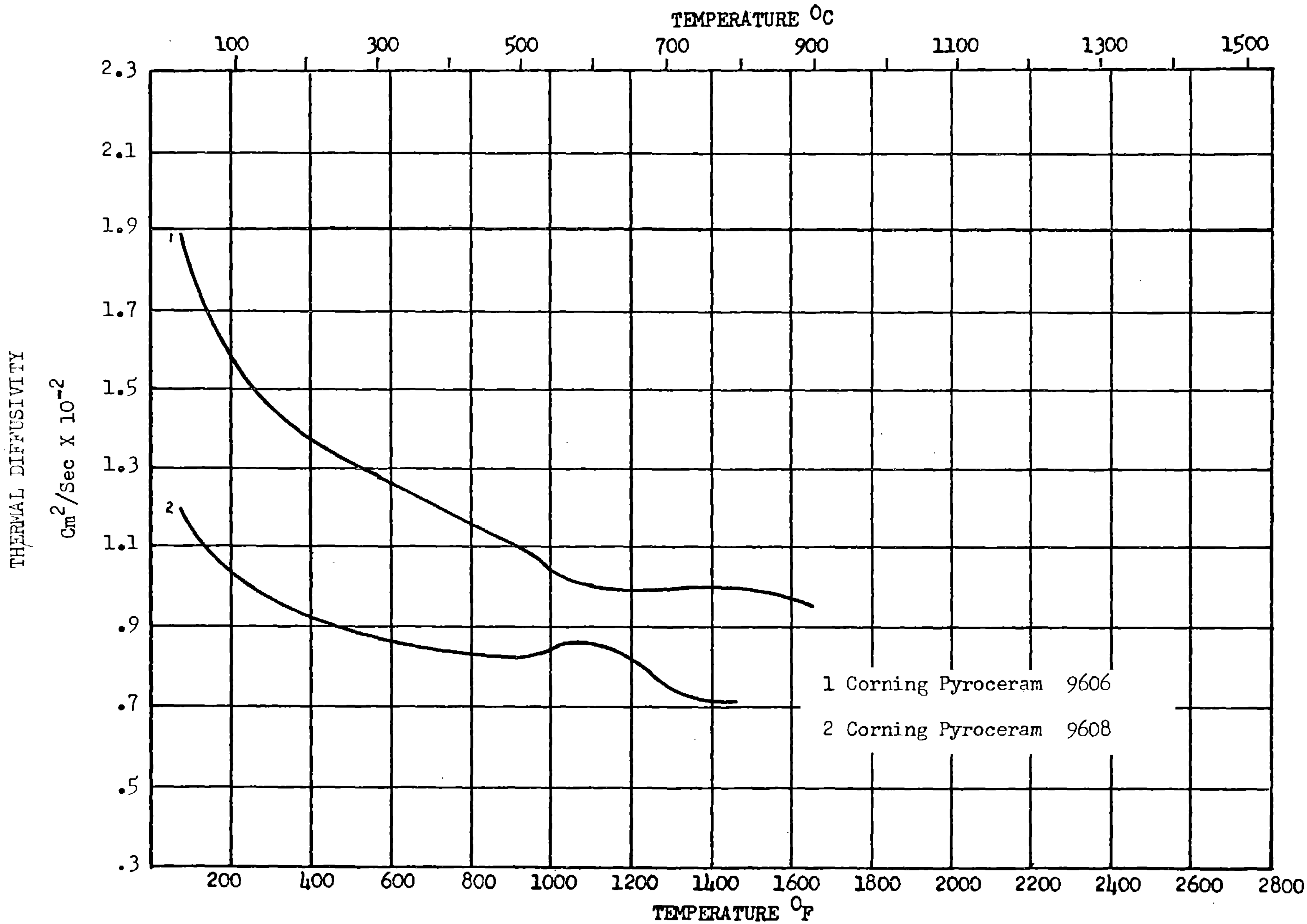

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
THERMAL DIFFUSIVITY
Cm²/Sec X 10⁻²
2.3
2.1
1.9
1.7
1.5
1.3
1.1
.9
.7
.5
.3
1
2
1 Corning Pyroceram 9606
2 Corning Pyroceram 9608
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 136

RD 1046

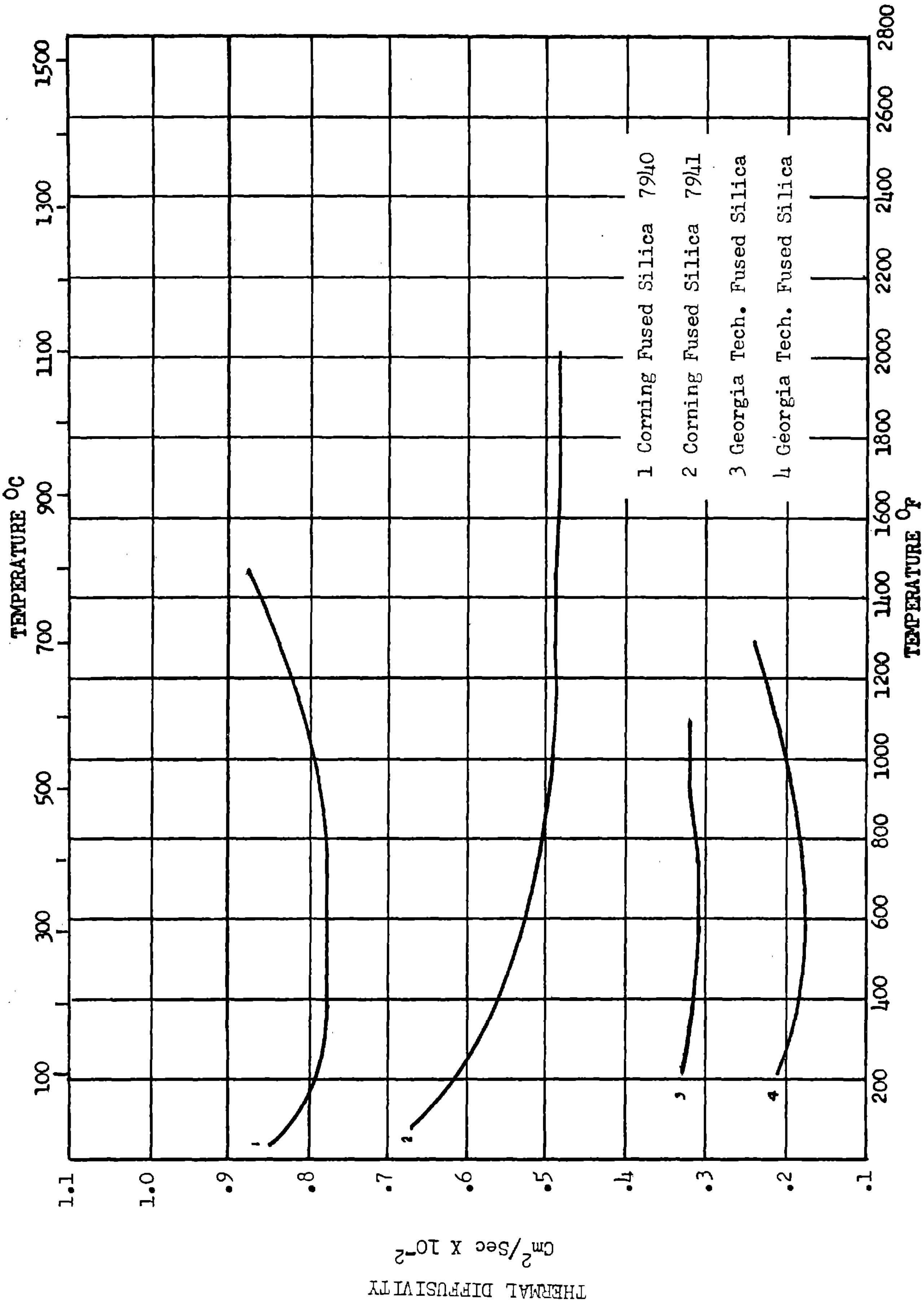


Figure 137

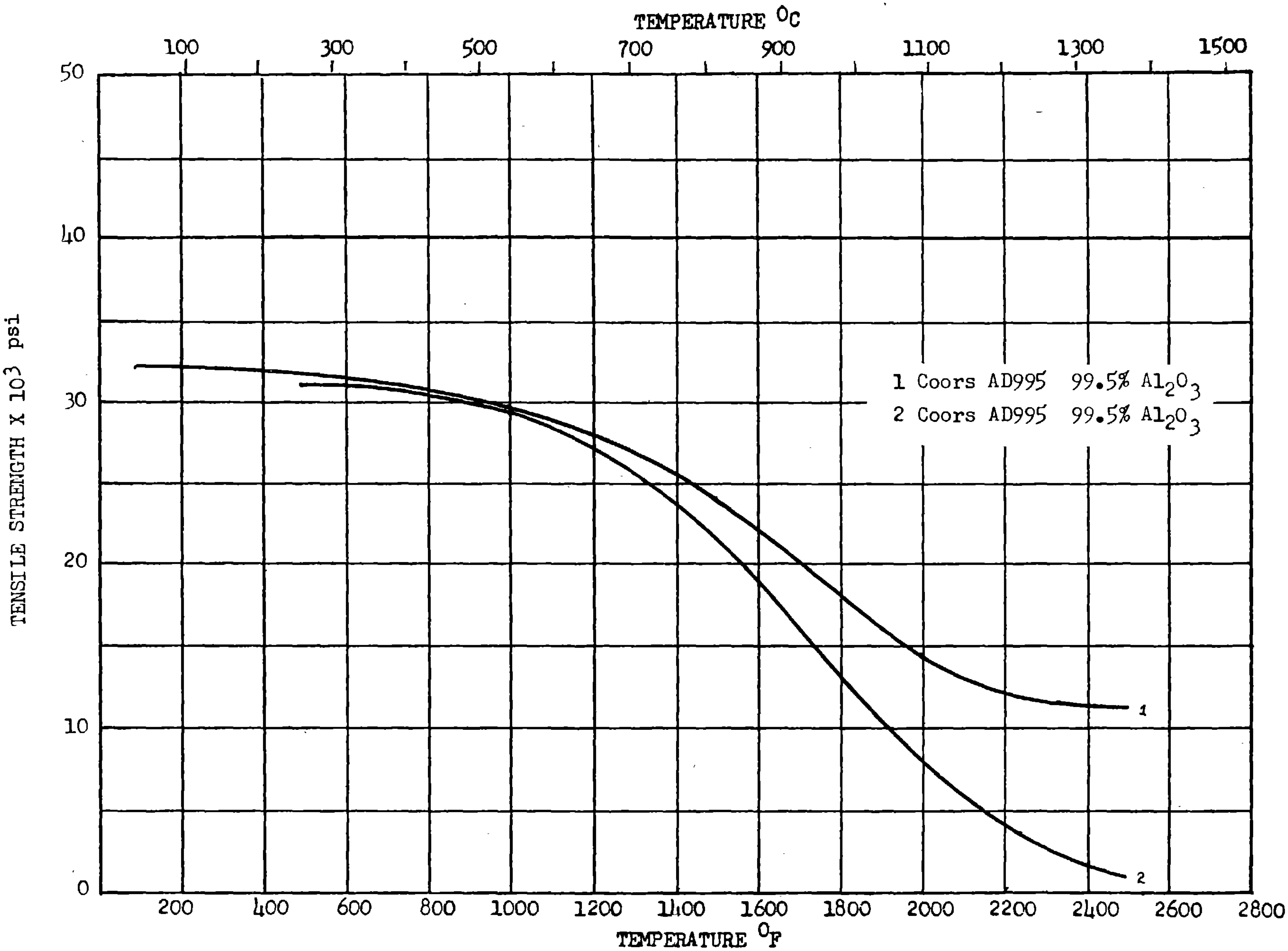

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
TENSILE STRENGTH X 10³ psi
50
40
30
20
10
0
1 Coors AD995 99.5% Al2O3
2 Coors AD995 99.5% Al2O3
1
2
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 138

RD 1046

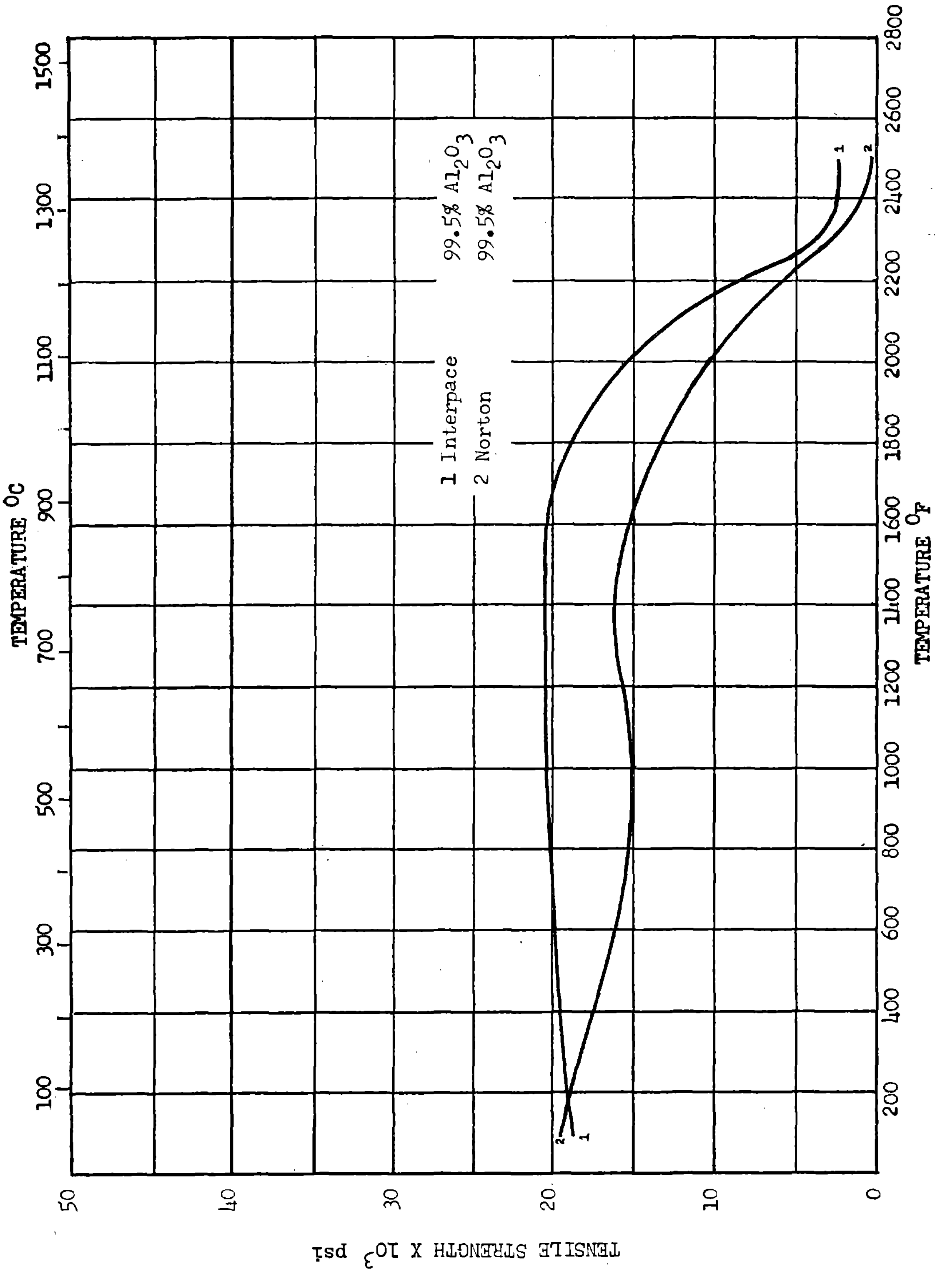


Figure 139

RD 1046

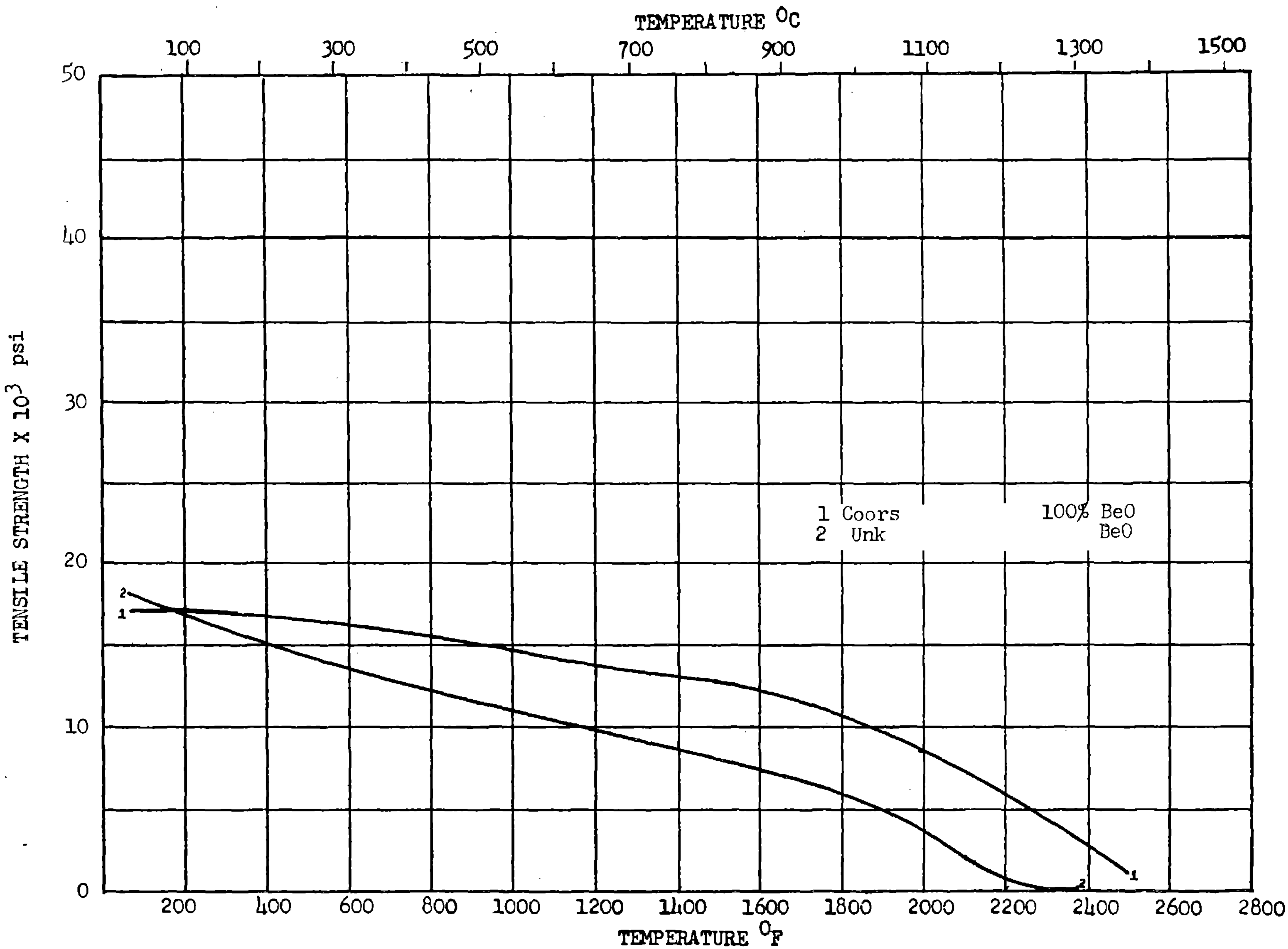


Figure 140

RD 1046

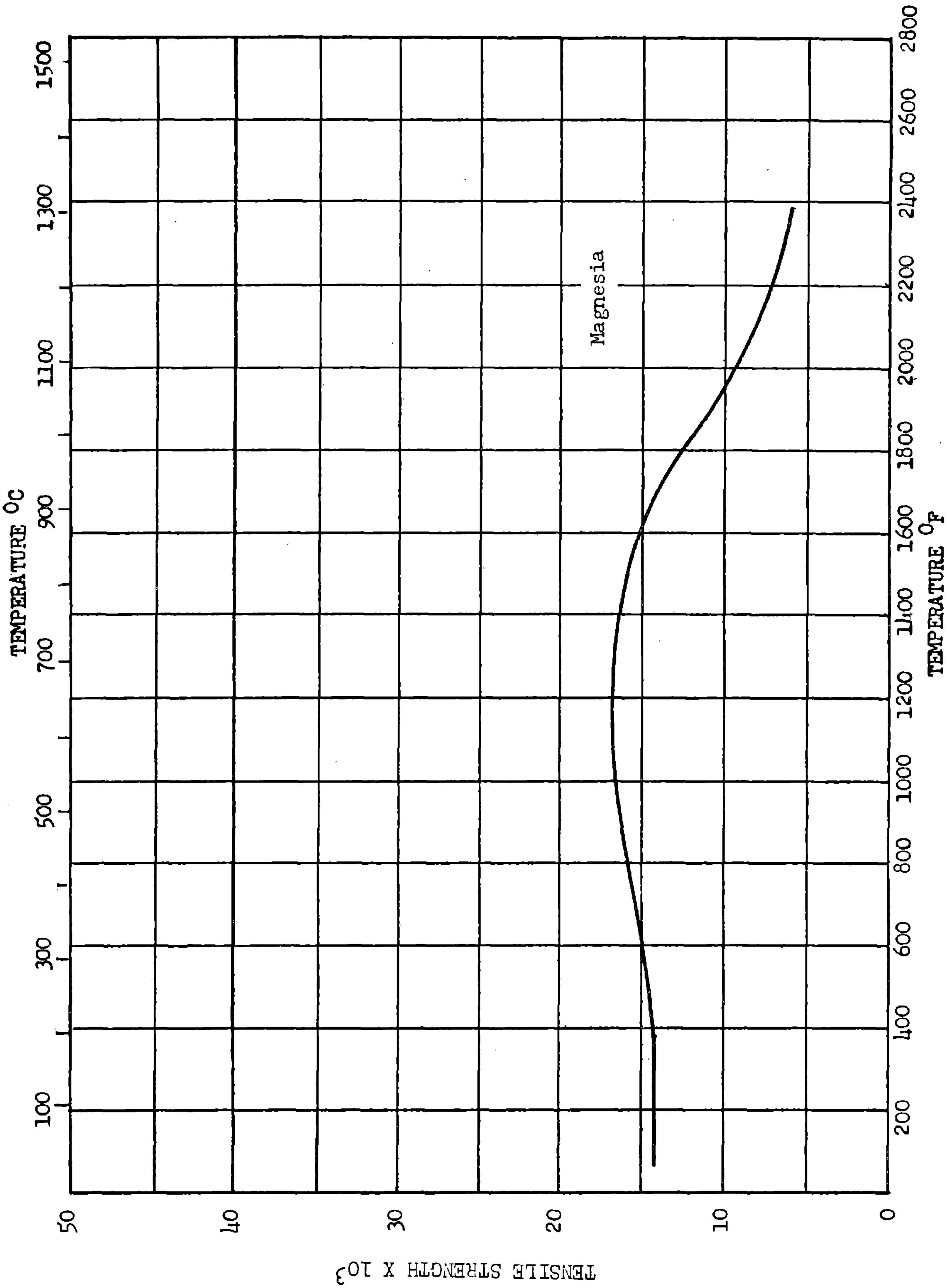


Figure 141

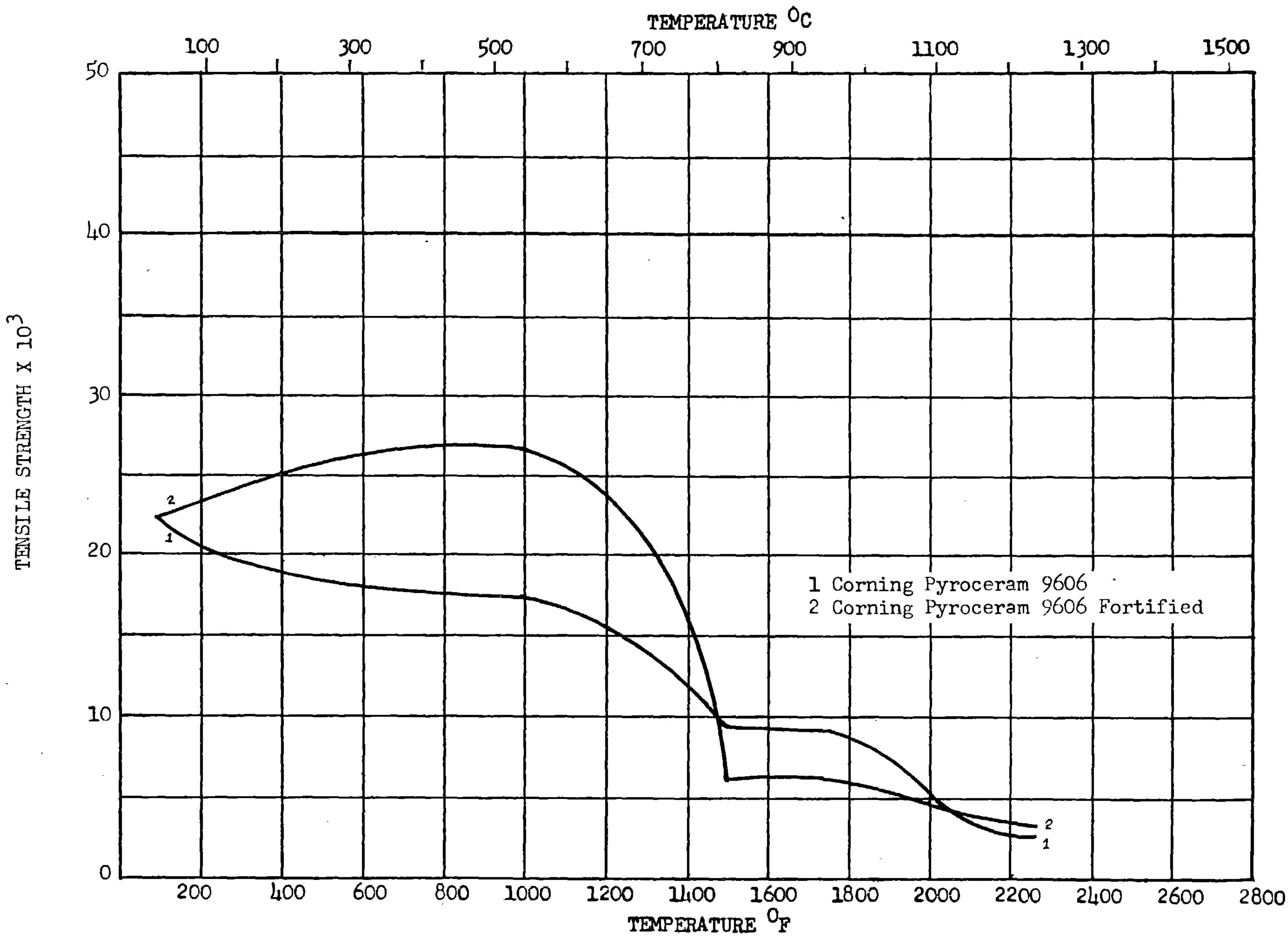

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
TENSILE STRENGTH X 10^3
0
10
20
30
40
50
1 Corning Pyroceram 9606
2 Corning Pyroceram 9606 Fortified
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 142

RD 1046

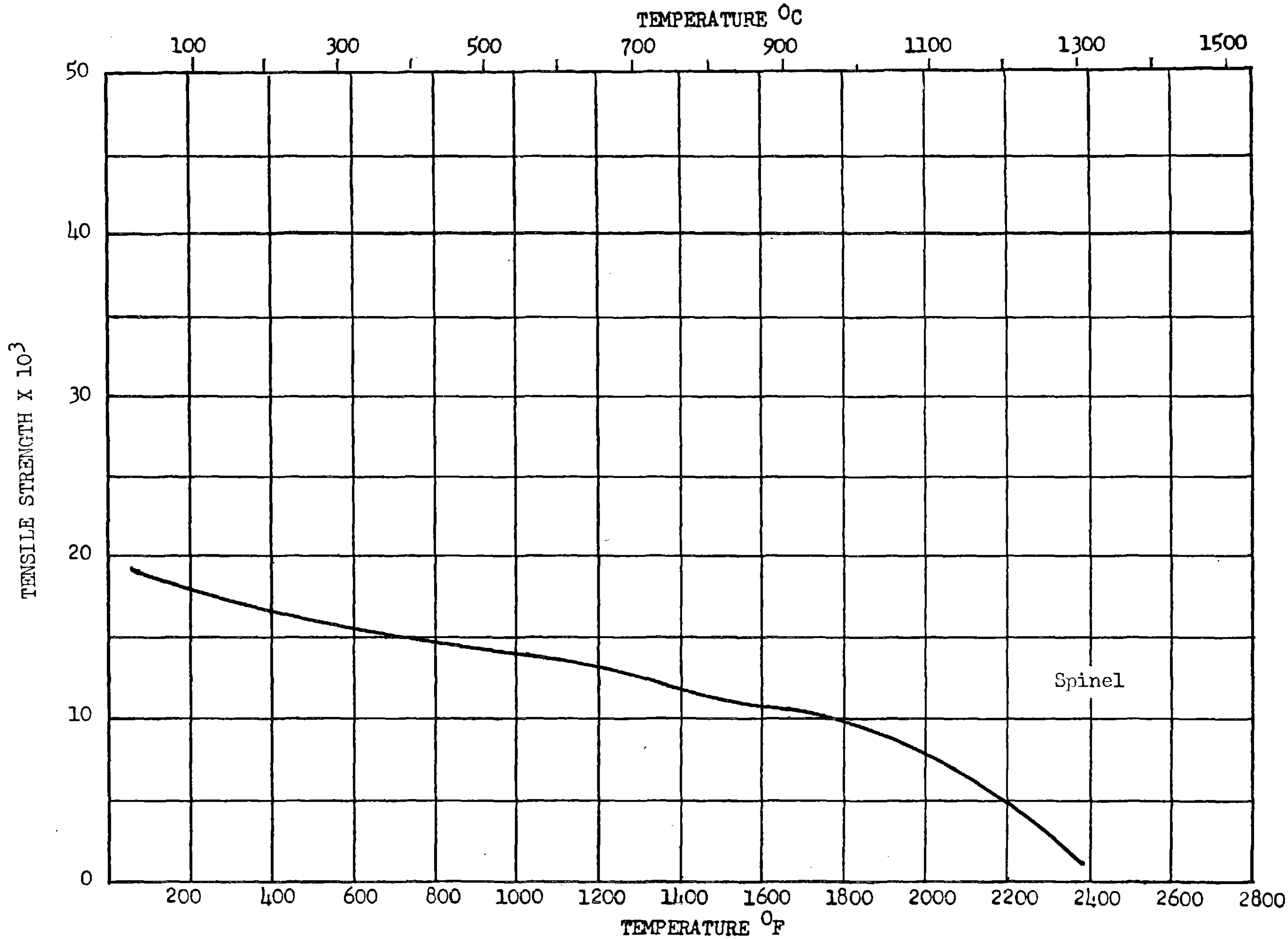


Figure 143

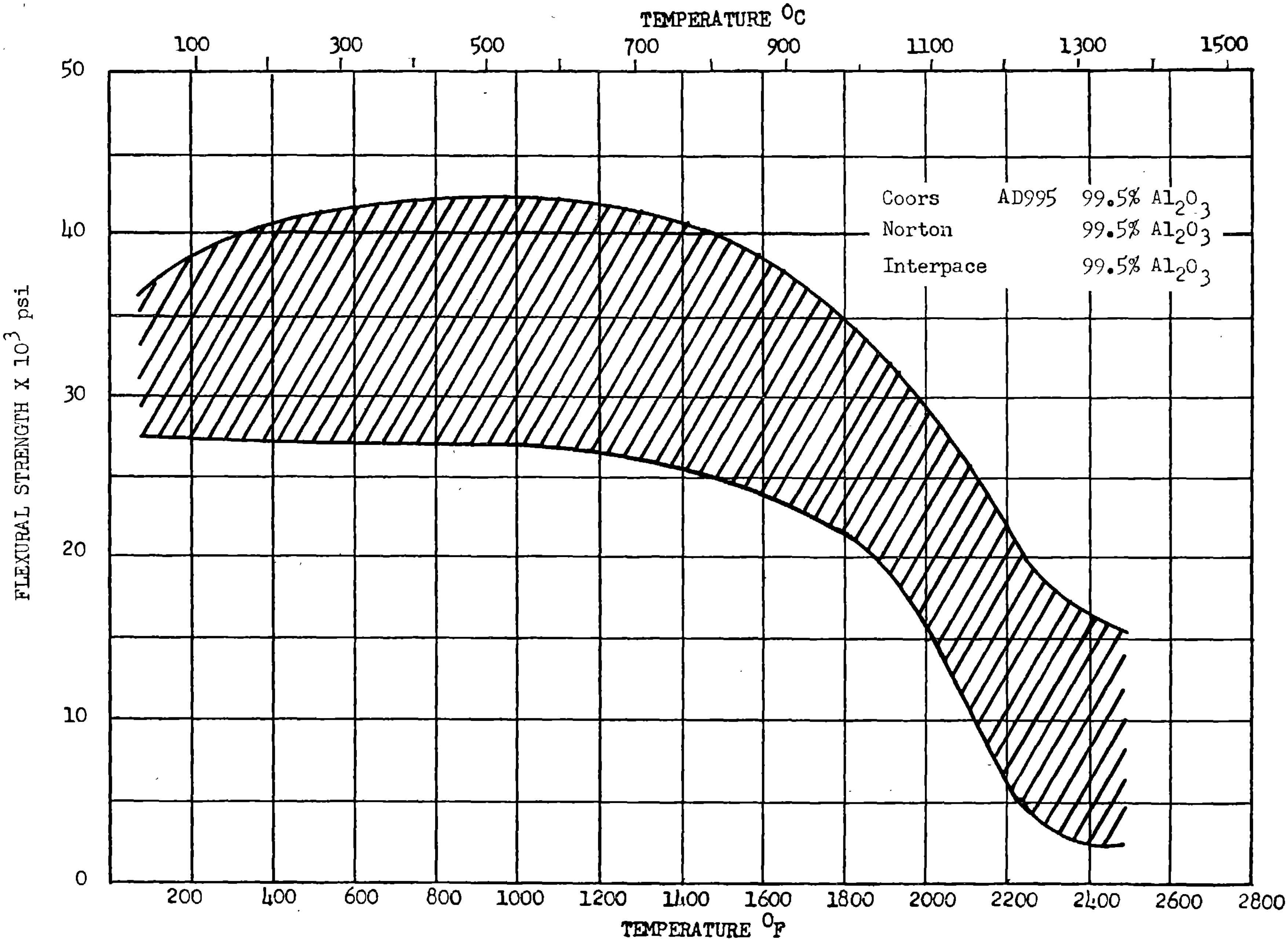

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
Coors AD995 99.5% Al_2O_3
Norton 99.5% Al_2O_3
Interpace 99.5% Al_2O_3
FLEXURAL STRENGTH X 10^3 psi
50
40
30
20
10
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 144

RD 1046

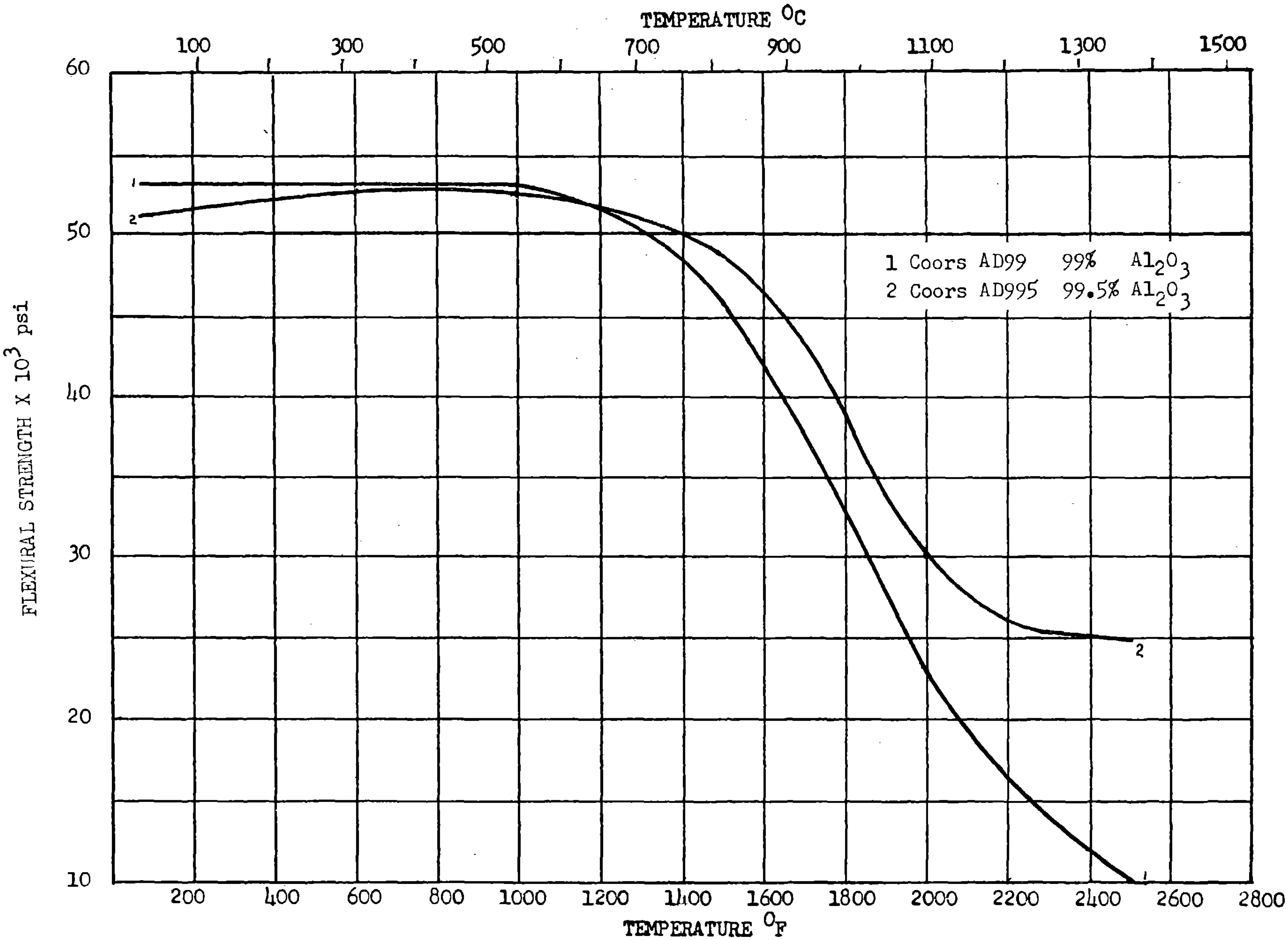


Figure 145

RD 1046

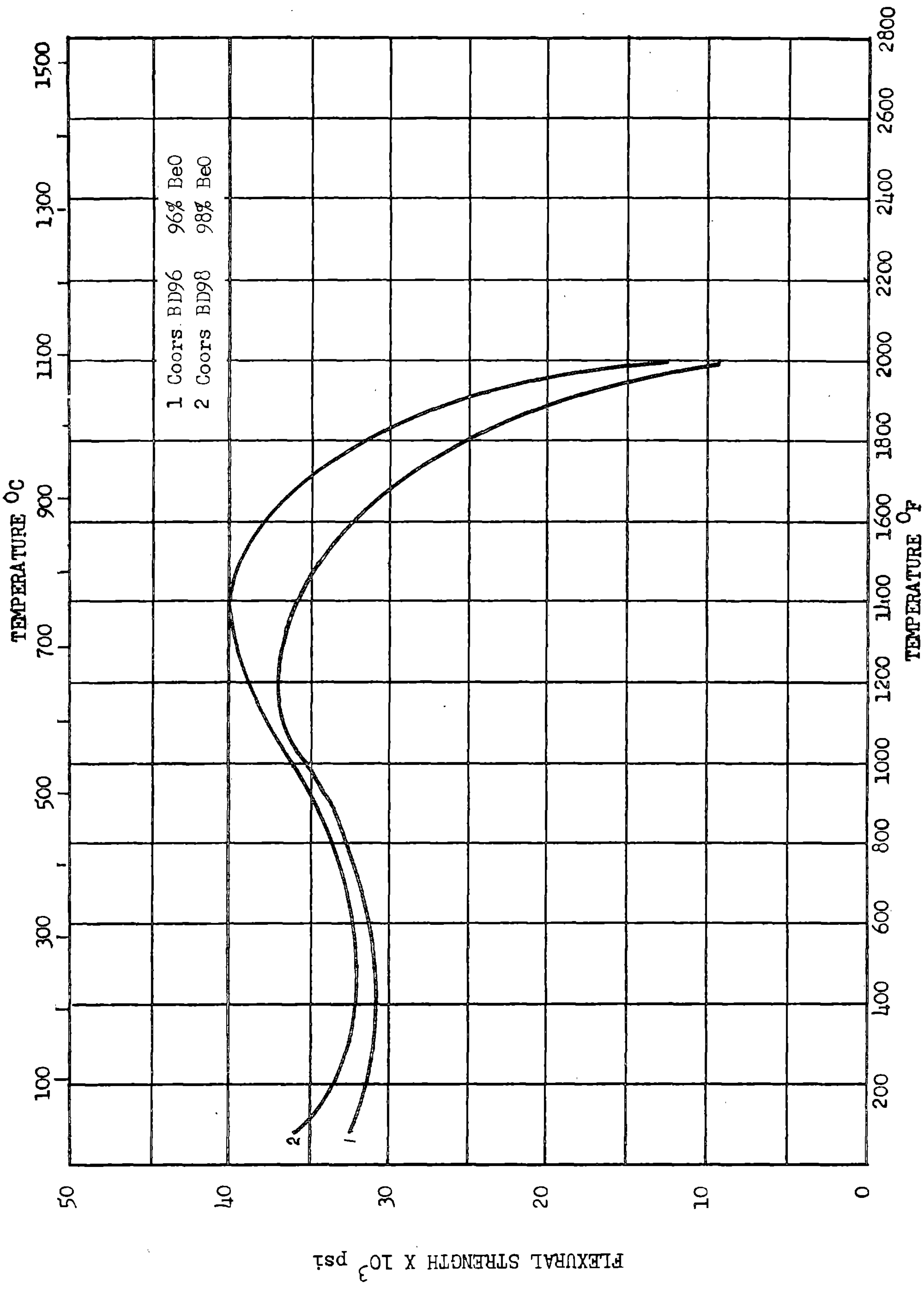


Figure 146

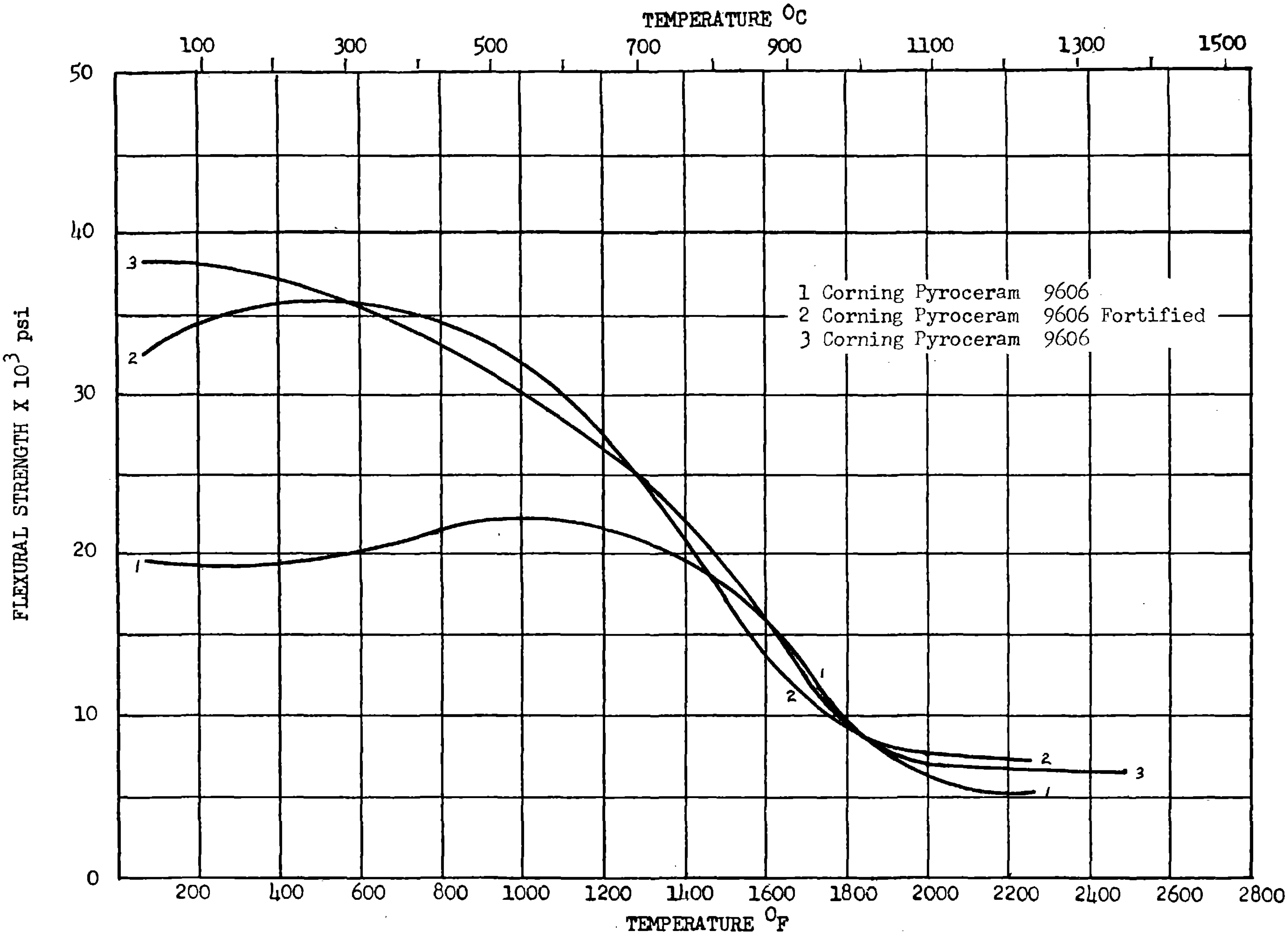

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
50
40
30
20
10
0
FLEXURAL STRENGTH X 10^3 psi
1 Corning Pyroceram 9606
2 Corning Pyroceram 9606 Fortified
3 Corning Pyroceram 9606
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 147

RD 1046

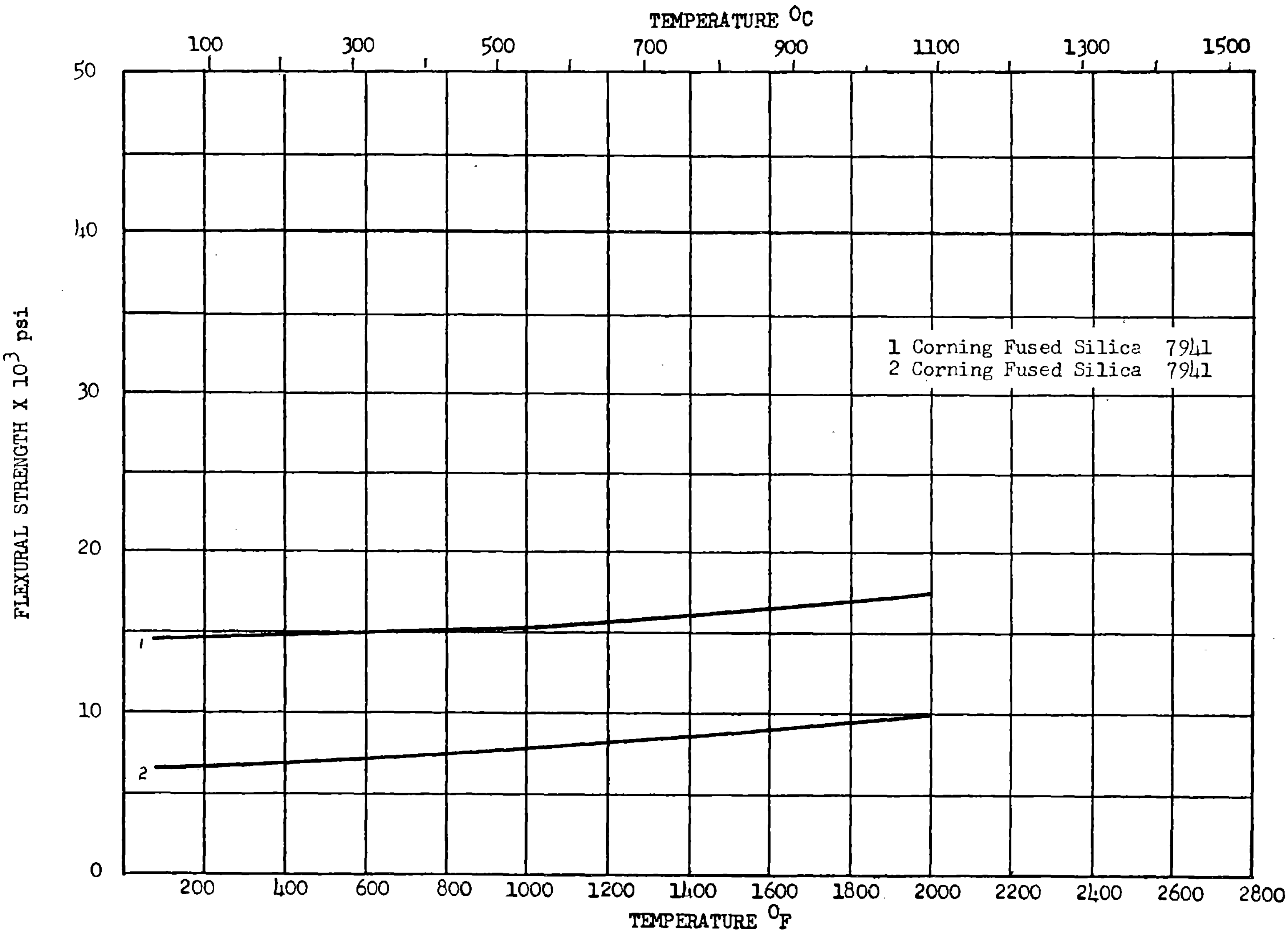


Figure 148

RD 1046

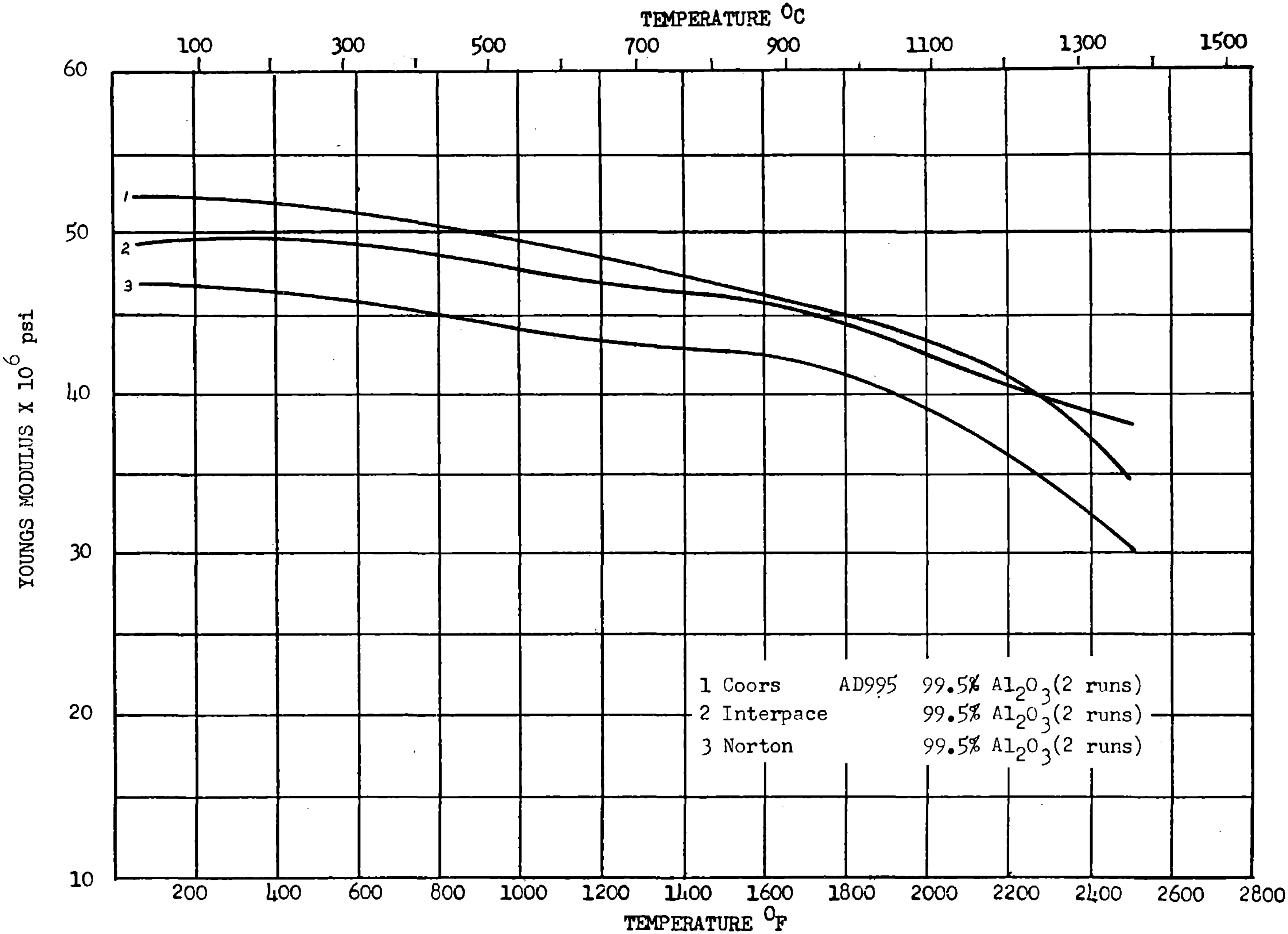


Figure 149

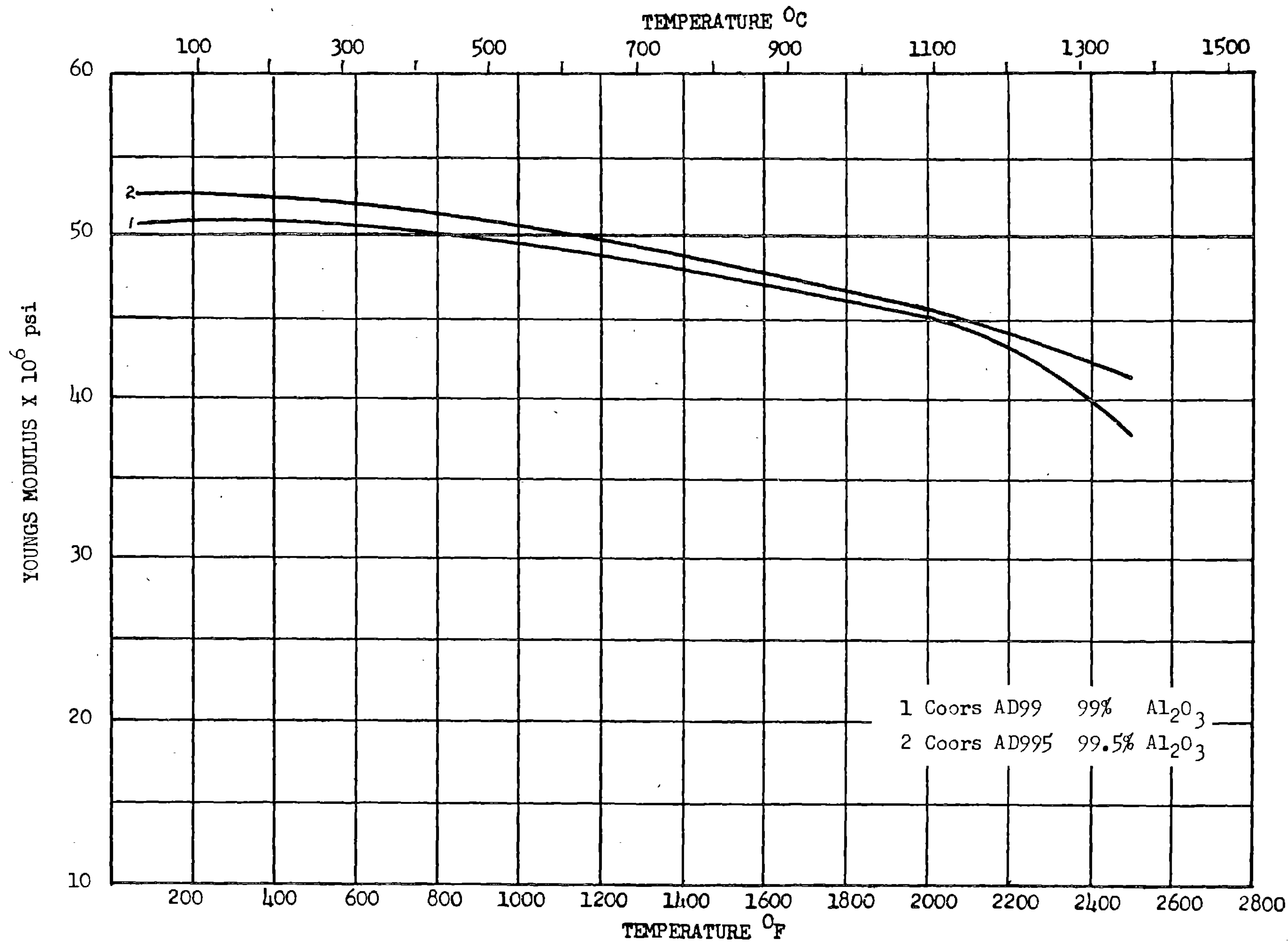

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
60
50
40
30
20
10
YOUNGS MODULUS X 10^6 psi
2
1
1 Coors AD99 99% Al2O3
2 Coors AD995 99.5% Al2O3
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 150

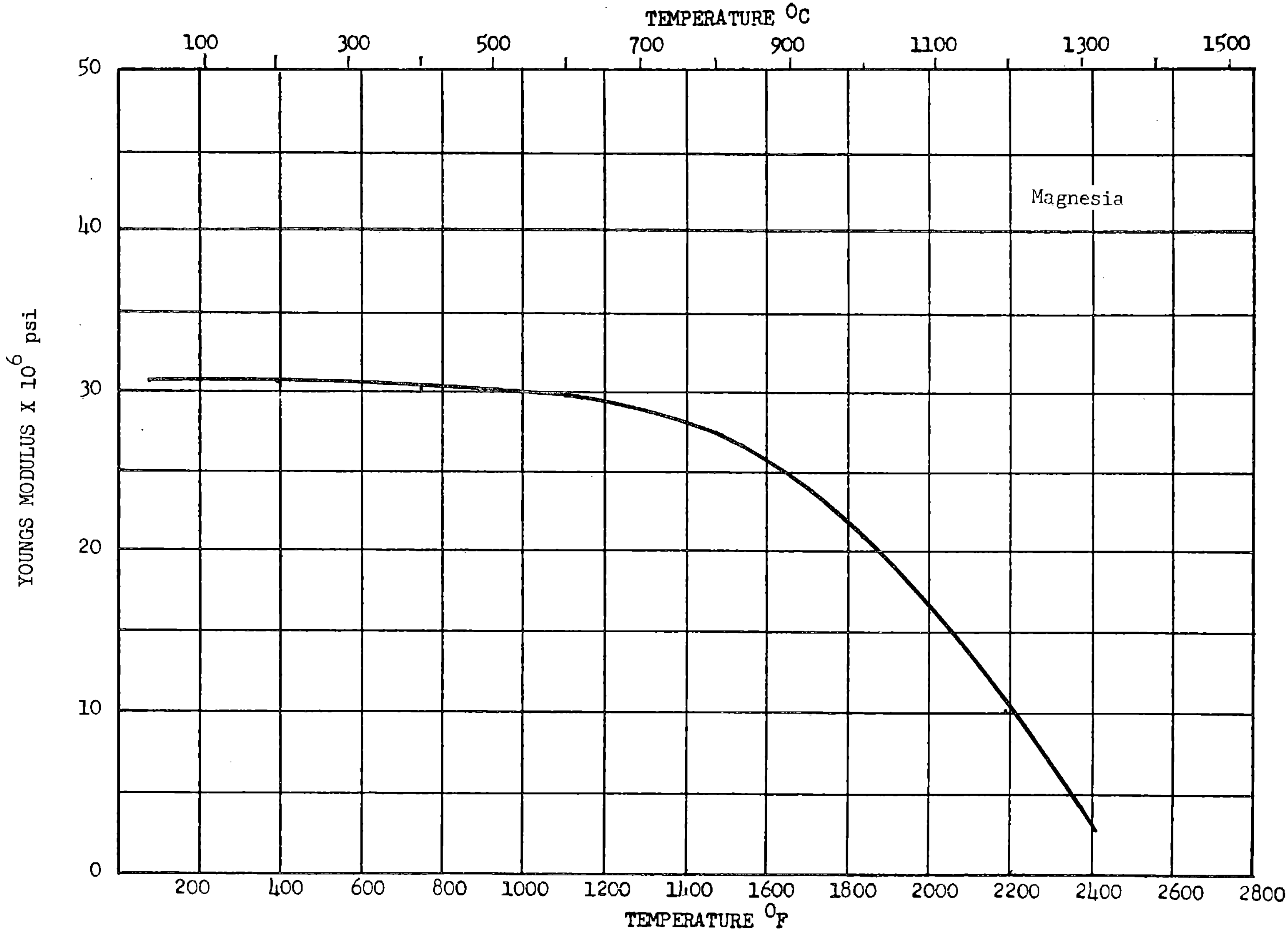

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
50
40
30
20
10
0
YOUNGS MODULUS X 10^6 psi
Magnesia
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 151

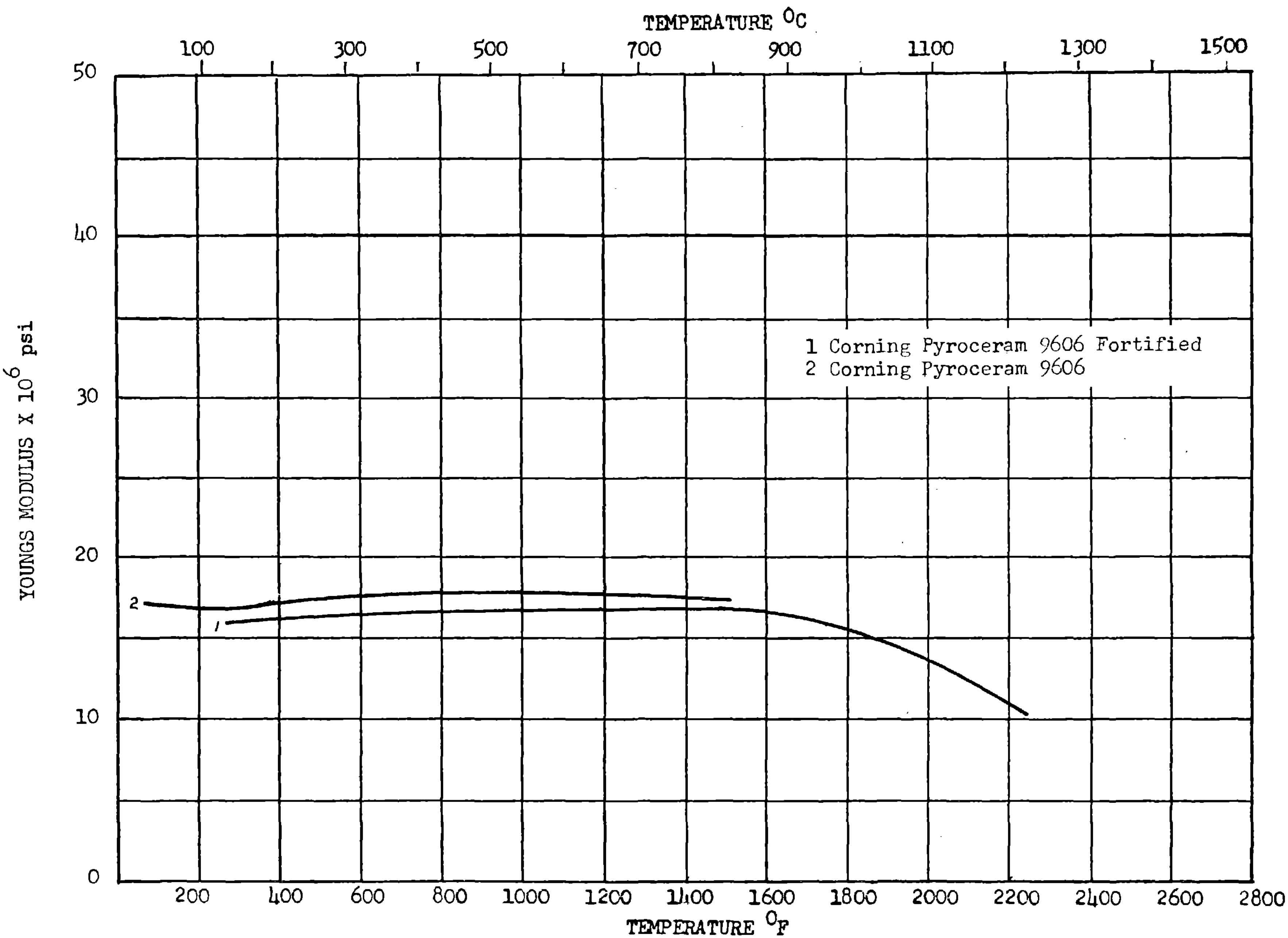

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
50
40
30
20
10
0
YOUNGS MODULUS X 10^6 psi
1 Corning Pyroceram 9606 Fortified
2 Corning Pyroceram 9606
2
1
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 152

RD 1046

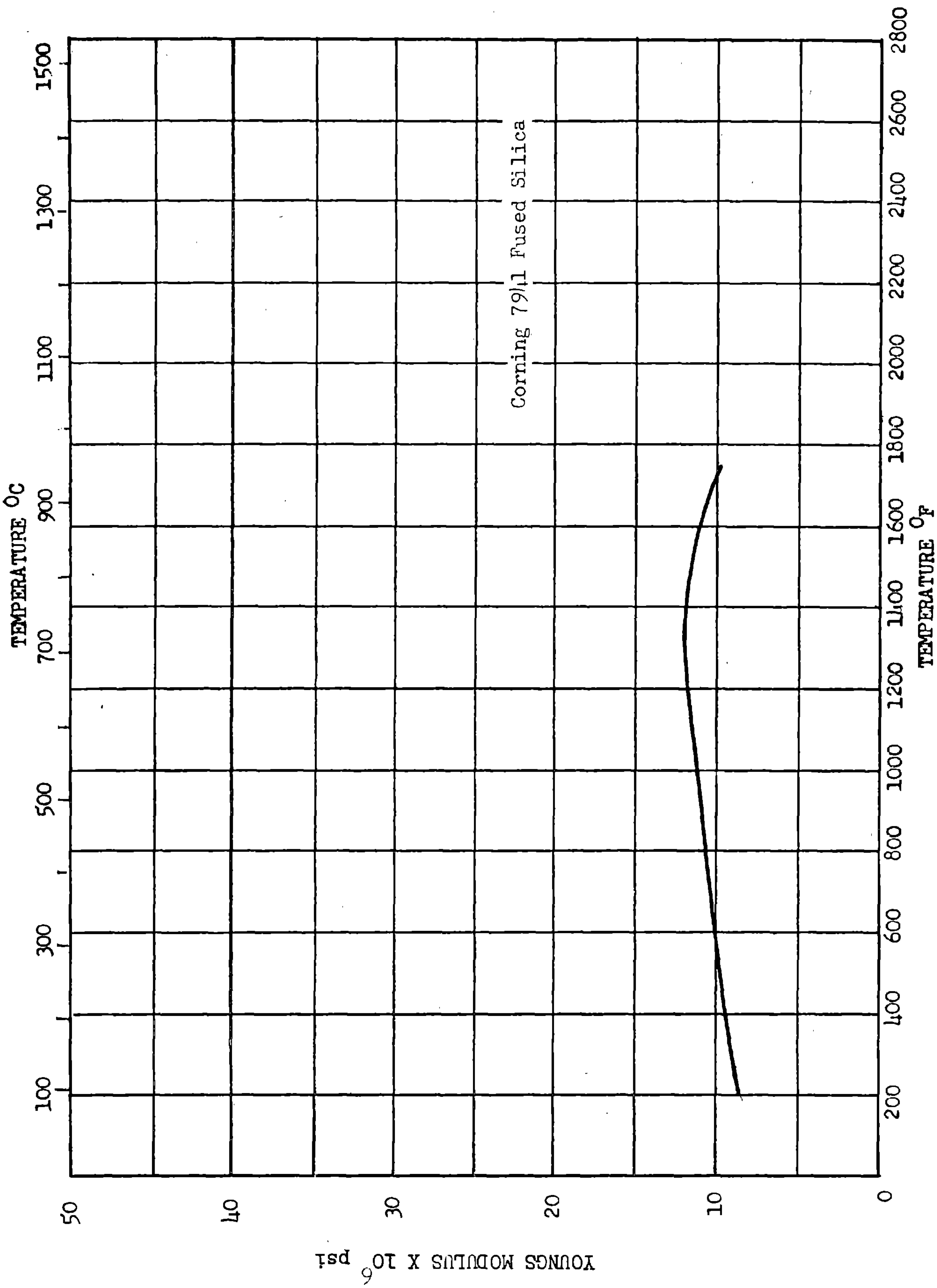


Figure 153

RD 1046

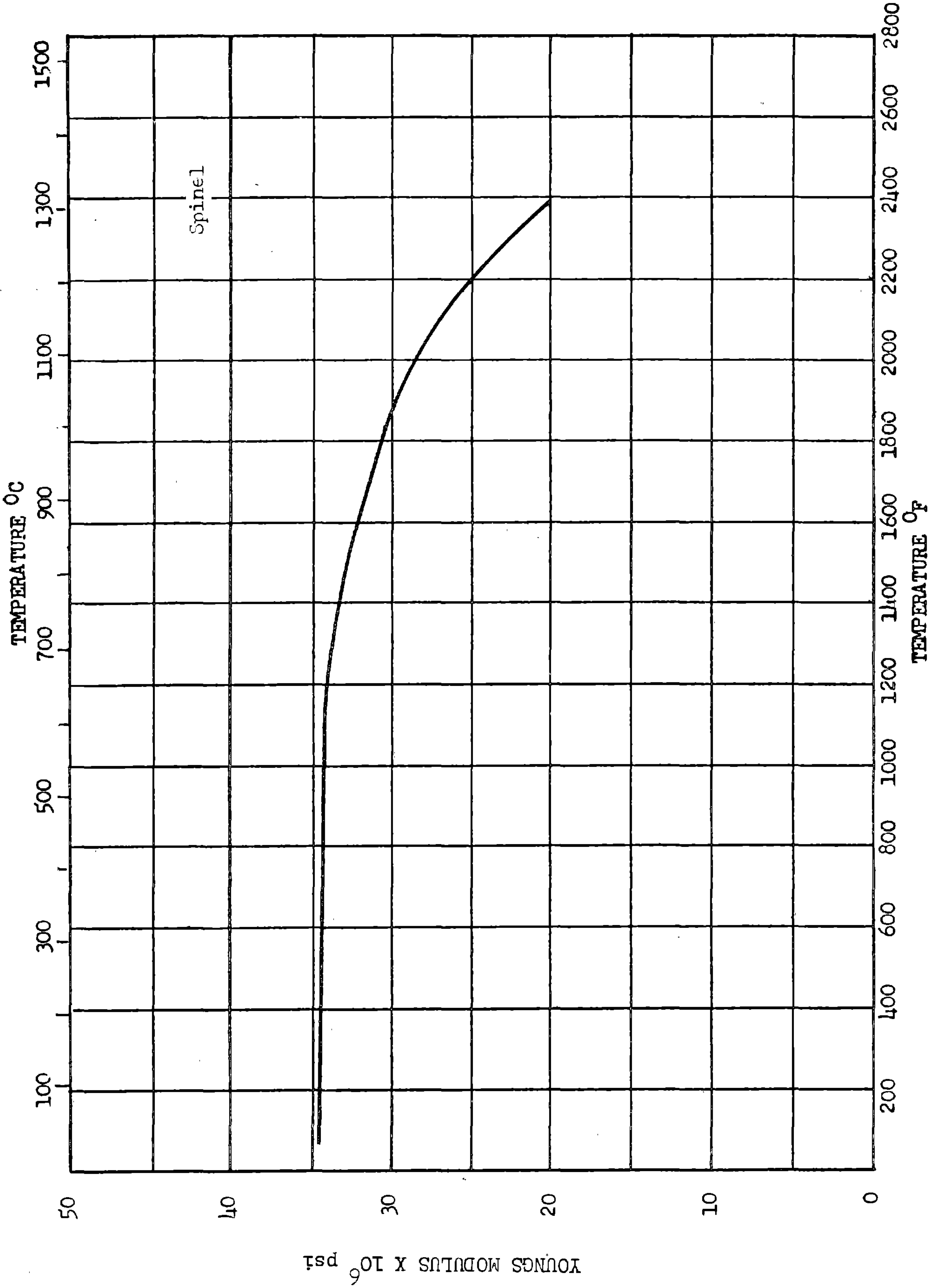


Figure 154

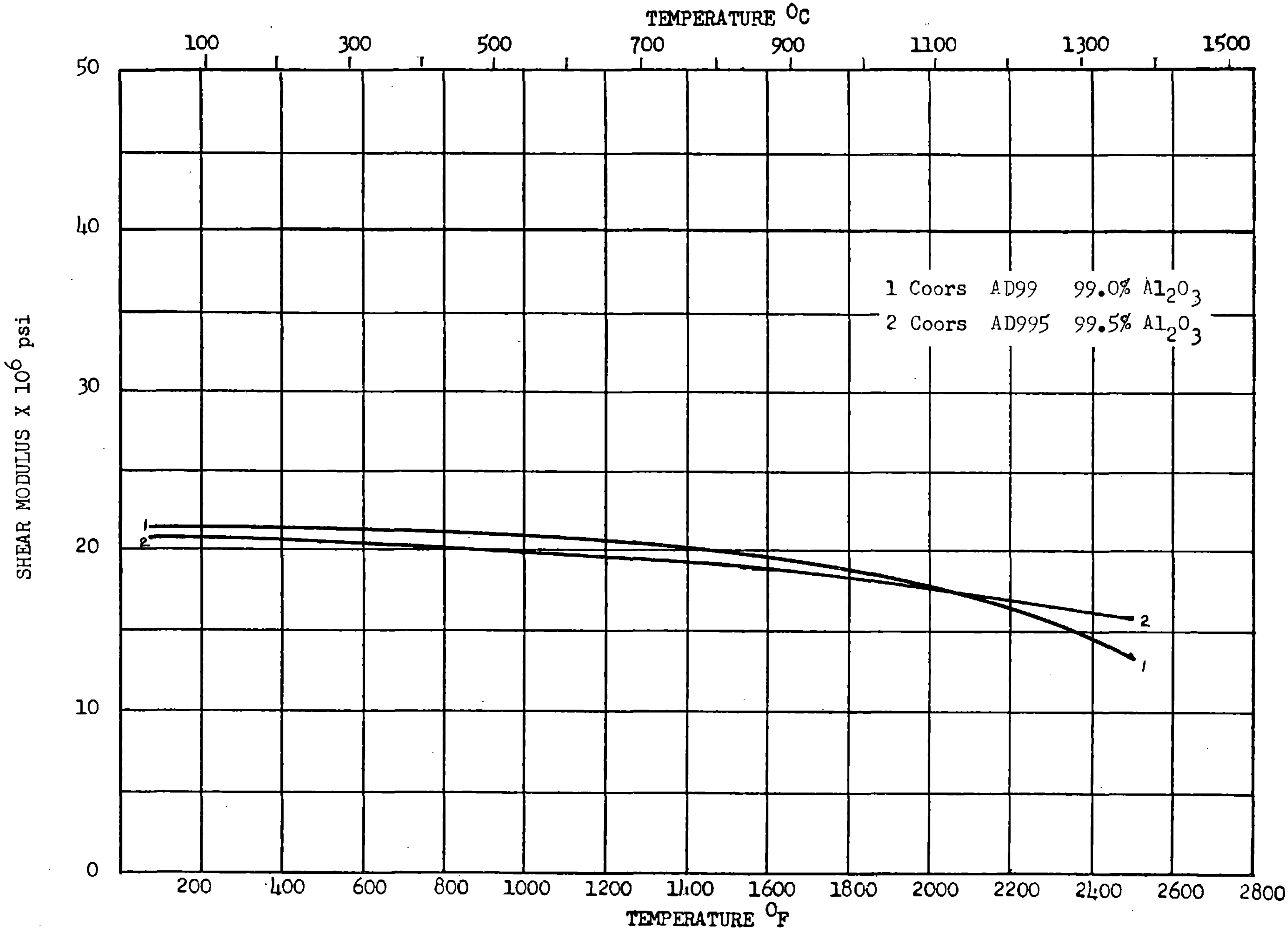

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
SHEAR MODULUS X 10^6 psi
50
40
30
20
10
0
1 Coors AD99 99.0% Al2O3
2 Coors AD995 99.5% Al2O3
1
2
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 155

RD 1046

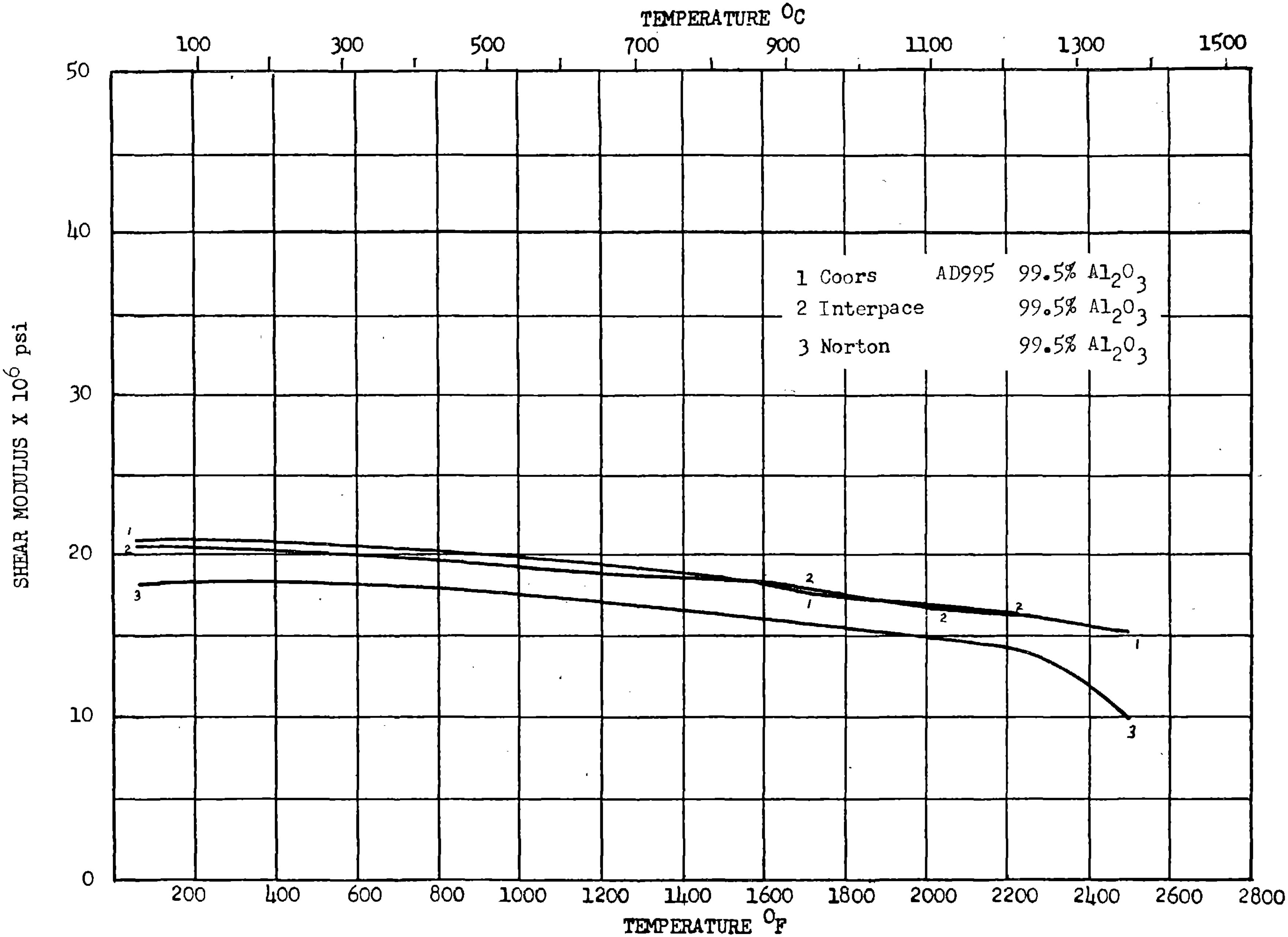


Figure 156

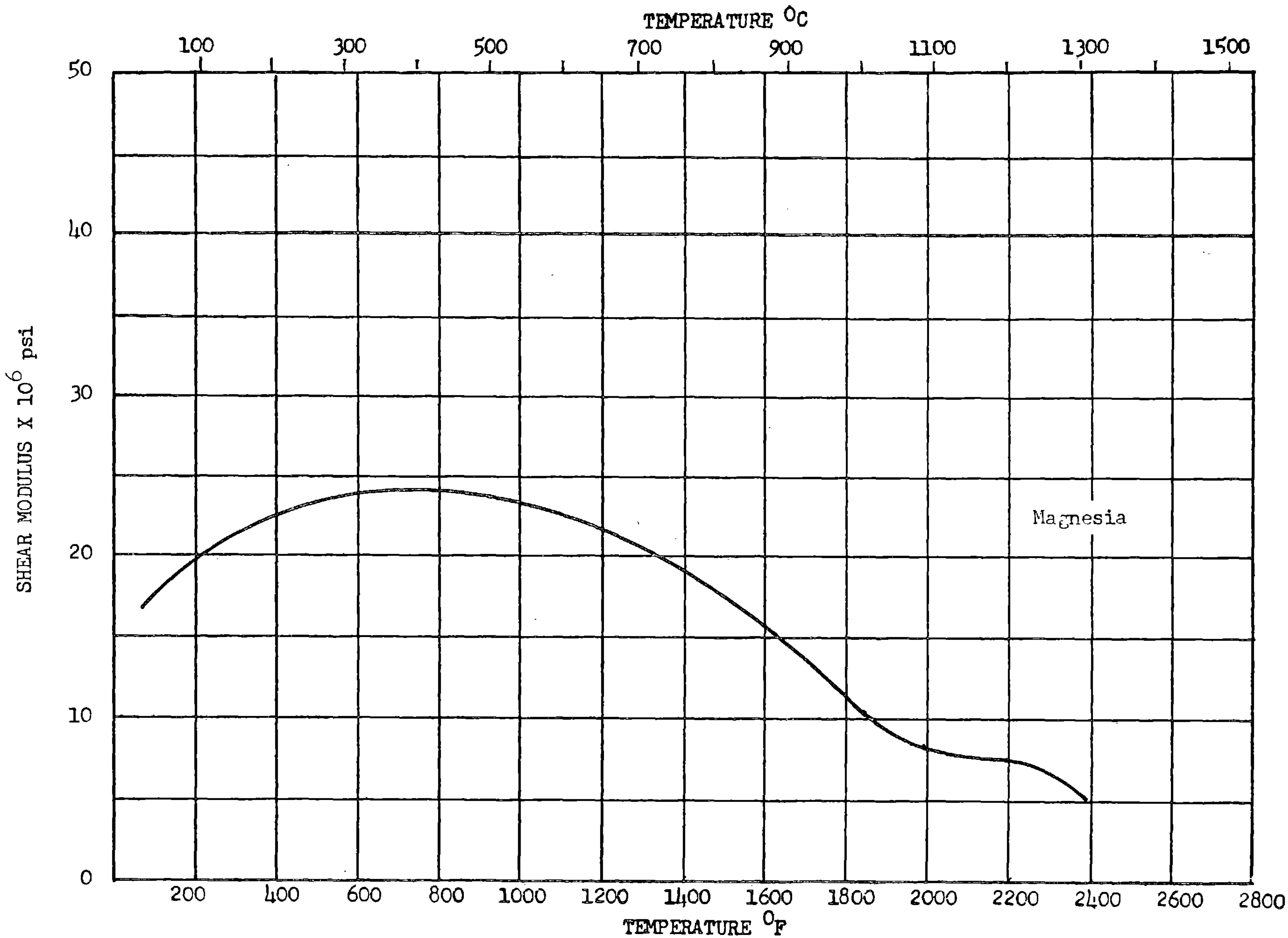
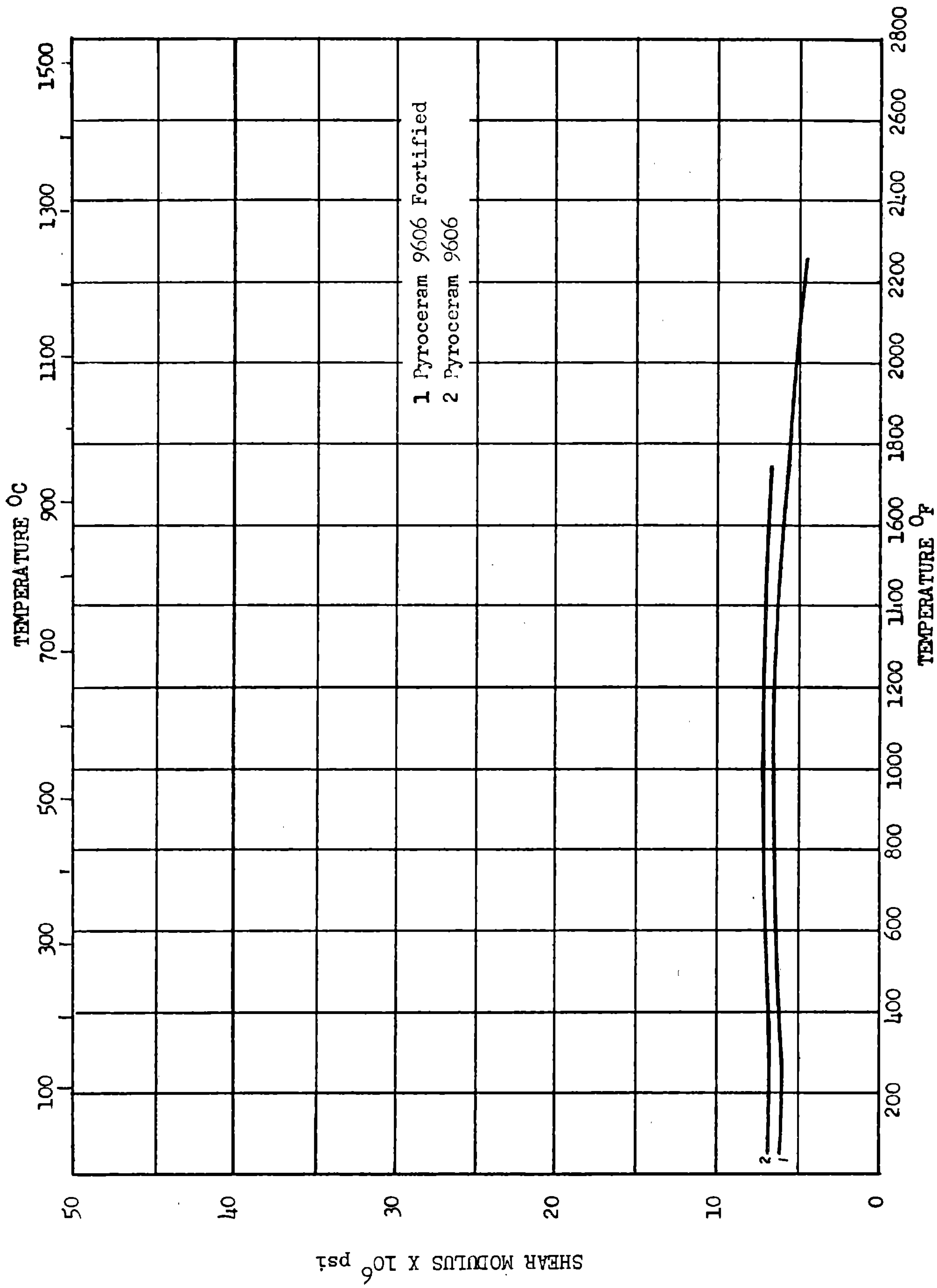

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
50
40
30
20
10
0
SHEAR MODULUS X 10^6 psi
Magnesia
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 157



TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
1 Pyroceram 9606 Fortified
2 Pyroceram 9606
SHEAR MODULUS X 10^6 psi
50
40
30
20
10
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 158

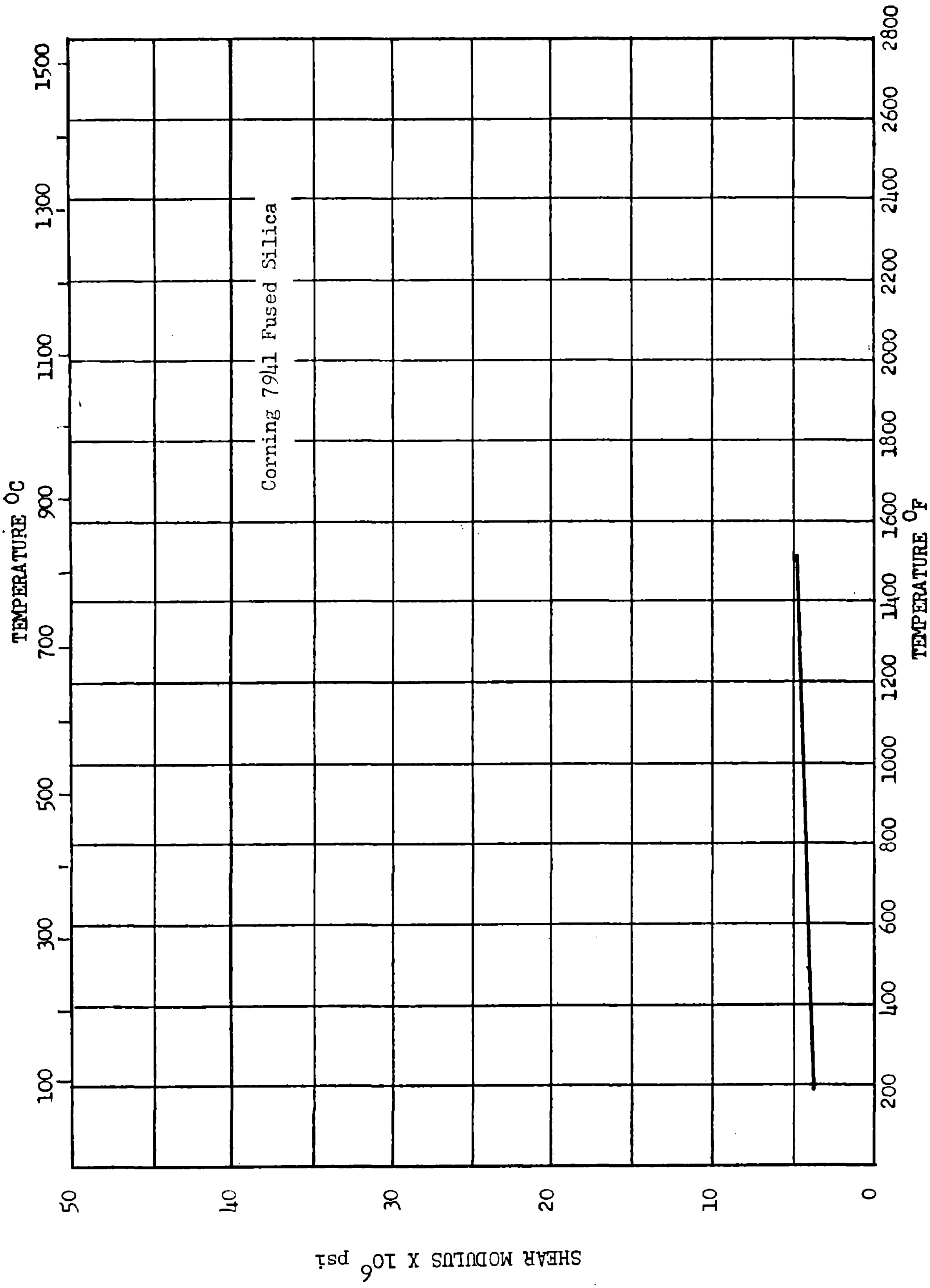

Corning 7941 Fused Silica
TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
TEMPERATURE °F
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
SHEAR MODULUS X 10^6 psi
0
10
20
30
40
50

Figure 159

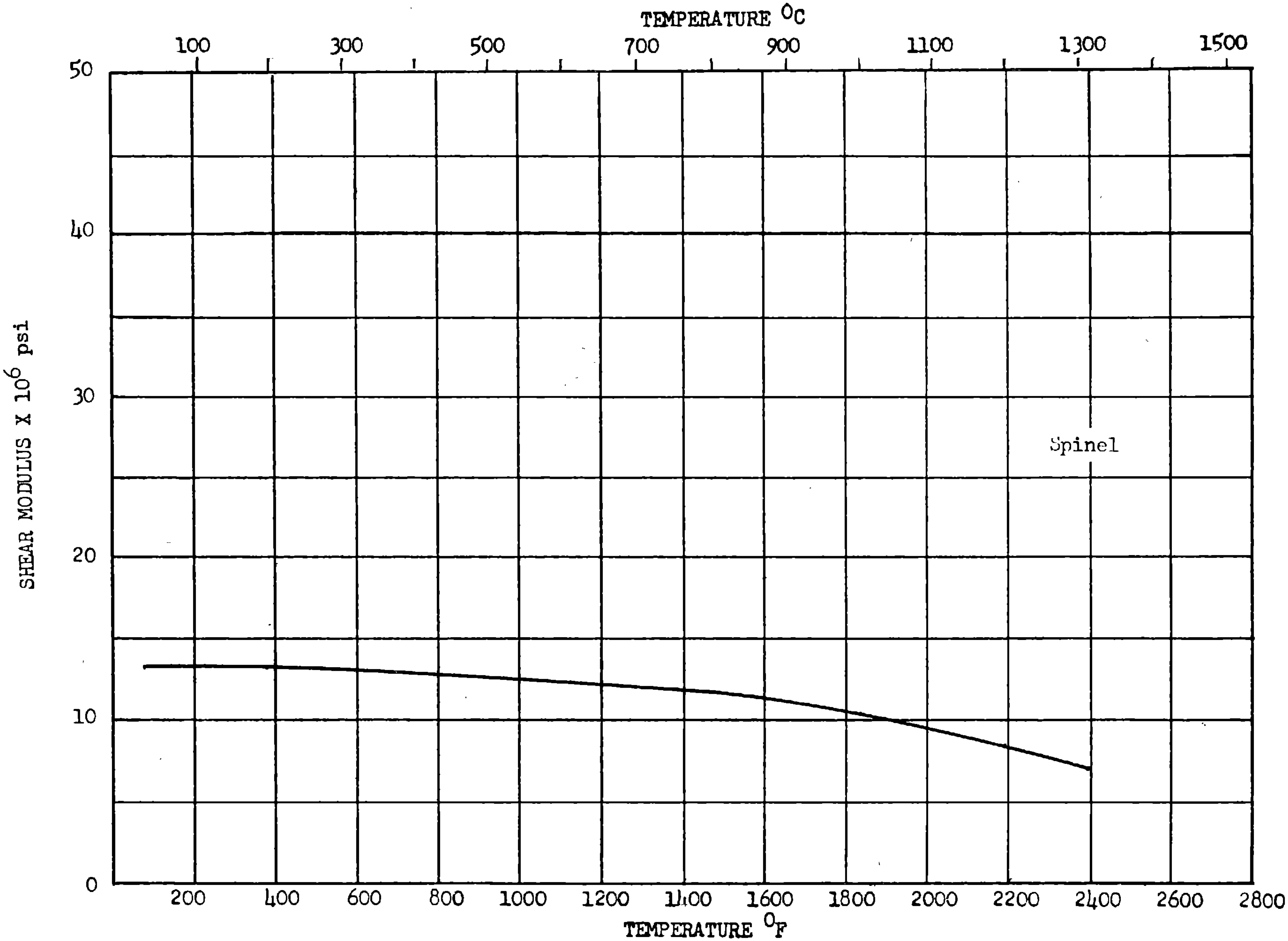

TEMPERATURE °C
100
300
500
700
900
1100
1300
1500
50
40
30
20
10
0
SHEAR MODULUS X 10^6 psi
Spinel
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
TEMPERATURE °F

Figure 160

SECTION B

TABULAR DATA

DIELECTRIC CONSTANT & LOSS TANGENT
ALUMINA

Item No.	Trade Designation	% Main Constituent	Temp °F	Dielectric Constant	Loss Tangent	Freq Gc
1	Alberox Corp. A962	-	78	9.09	.00065	3.87-3.67
			200	9.15	.00070	
			400	9.29	.00080	
			800	9.53	.00170	
			1200	9.83	.00380	
			1400	10.02	.00600	
2	American Lava 614	96.0	78	9.31	.00080	3.53-3.15
			200	9.39	.00095	
			400	9.56	.00125	
			800	9.84	.00200	
			1200	10.25	.00340	
			1600	10.71	.00590	
			1800	11.00	.00825	
3	American Lava 614	96.0	78	8.51	.00070	25
			400	8.65		
			800	8.88		
			1200	9.27		
			1400	9.55		
4	American Lava 614	96.0	78	8.60	.00290	10
			400	8.93		
			800	9.25		
			1200	9.72		
			1400	10.00		
5	American Lava 719	94.0	78	9.00	.00095	3.67-3.40
			200	9.07	.00085	
			400	9.21	.00075	
			800	9.48	.00070	
			1200	9.81	.00105	
			1600	10.27	.00350	
			1800	10.68	.01000	
6	American Lava	94.0	78	8.05	.00130	25
			400	8.20		
			800	8.38		
			1000	8.48		
7	American Lava	94.0	78	8.25	.00070	25
			400	8.30		
			800	8.40		
			1000	~ 8.63		

Item No.	Trade Designation	% Main Constituent	Temp °F	Dielectric Constant	Loss Tangent	Freq Gc
8	American Lava	94.0	78	8.42	.00220	10
			400	8.65		
			800	8.83		
			1200	9.30		
			1400	9.60		
9	American Lava 576	85.0	78	8.18	.00120	3.79-3.57
			200	8.23	.00140	
			400	8.37	.00160	
			800	8.62	.00210	
			1200	8.96	.00340	
			1600	9.29	.00420	
			1800	9.32	.00430	
10	Carborundum 1542	96.0	78	9.20	.00048	3.83-3.47
			200	9.28	.00049	
			400	9.43	.00055	
			800	9.72	.00120	
			1200	10.14	.00130	
			1600	10.64	.00260	
			1800		.00340	
			2000	11.20	.01000	
11	Coors AD995	99.5	78	9.63	.00008	3.80-3.33
			200	9.75	.00009	
			400	9.97	.00011	
			800	10.35	.00020	
			1200	10.76	.00025	
			1600	11.18	.00047	
			2000	11.59	.00083	
			2400	12.06	.00190	
12	Coors AD995	99.5	78	9.62	.00021	9.375
			400	9.83	.00023	
			800	10.09	.00027	
			1200	10.24	.00031	
			1600	10.61	.00037	
			2000	10.87	.00050	
			2400	10.11	.00100	
			2600	11.26	.00250	
			2700	11.34	.01000	
13	Coors AD99	99.0	78		.00022	9.375
			200	9.66	.00023	
			400	9.78	.00024	
			800	10.03	.00028	
			1200	10.28	.00034	
			1600	10.44	.00048	
			2000	10.81	.00105	
			2400	11.09	.00325	

Item No.	Trade Designation	% Main Constituent	Temp °F	Dielectric Constant	Loss Tangent	Freq Gc
14	Coors AD99	99.0	78	9.47	.00020	4.13-3.71
			200	9.56	.00021	
			400	9.70	.00023	
			800	9.97	.00025	
			1200	10.29	.00030	
			1600	10.63	.00080	
			2000	11.20	.00220	
			2400	11.47	.01000	
15	Coors MC2014	-	78	9.42	.00034	3.86-3.58
			200	9.49	.00035	
			400	9.61	.00036	
			800	9.90	.00043	
			1200	10.21	.00060	
			1600	10.59	.00120	
			1800	10.81	.00170	
16	Coors RR	--	78	9.42	.00022	3.94-3.71
			200	9.50	.00030	
			400	9.60	.00040	
			800	9.88	.00085	
			1200	10.19	.00295	
			1400	10.36	.00625	
17	Diamonite P-3142-1	95.0-97.0	78	9.18	.00065	3.67-3.38
			200	9.25	.00063	
			400	9.39	.00062	
			800	9.69	.00085	
			1200	10.08	.00270	
			1600	10.52	.00460	
			1800	10.82	.01000	
18	Diamonite B-890-2	90.0-95.0	78	8.74	.00115	3.73-3.44
			200	8.81	.00115	
			400	8.95	.00120	
			800	9.20	.00145	
			1200	9.51	.00250	
			1600	10.00	.00600	
			1800	10.30	.01000	
19	Diamonite P-3662	85.0-90.0	78	8.40	.00150	3.82-3.53
			200	8.47	.00140	
			400	8.60	.00142	
			800	8.88	.00180	
			1200	9.20	.00350	
			1400		.00490	
			1600	9.56	.00520	
			1800	9.80	.01000	

Item No.	Trade Designation	% Main Constituent	Temp °F	Dielectric Constant	Loss Tangent	Freq Gc
20	G.E. Lucalox	-	78	10.00		9.375
			200	10.10	.00030	
			400	10.25	.00070	
			800	10.55	.00190	
			1200	10.86	.00350	
			1600	11.15	.00460	
			1800	11.37	.00500	
21	G.E. Lucalox	-	78	10.02	.00045	3.07-3.00
			200	10.15	.00099	
			400	10.37	.00235	
			600	10.54	.00500	
			700	10.63	.01000	
22	Interpace TC352	99.0	78	9.50	.00019	9.375
			200	9.58	.00019	
			400	9.71	.00020	
			800	9.96	.00021	
			1200	10.22	.00024	
			1600	10.46	.00030	
			2000	10.71	.00044	
			2400	11.01	.00120	
			2600	11.20	.00380	
23	Interpace TC352	99.0	78	8.40	.00030	9.375
			500	8.58	.00040	
			1000	8.88	.00065	
			1200	8.99	.00080	
24	Interpace TC351	97.6	78	8.24	.00070	9.375
			500	8.42	.00135	
			1000	8.72	.00250	
			1200	8.82	.00345	
25	Minn.-Honeywell A203	95.0	78	8.63	.00097	3.77-3.57
			200	8.68	.00101	
			400	8.79	.00135	
			800	9.05	.00230	
			1200	9.18	.00425	
			1600	9.78	.00800	
			1700	9.90	.01000	
26	Minn.-Honeywell A127	85.0	78	7.94	.00162	4.05-3.77
			200	7.98	.00165	
			400	8.12	.00180	
			800	8.39	.00230	
			1200	8.78	.00355	
			1400	9.00	.00530	

Item No.	Trade Designation	% Main Constituent	Temp °F	Dielectric Constant	Loss Tangent	Freq Gc
27	National Beryllia Alox	-	78	9.11	.00017	3.64-3.33
			200	9.17	.00020	
			400	9.32	.00035	
			800	9.60	.00077	
			1200	9.94	.00175	
			1600	10.30	.00320	
			2000	10.71	.00640	
28	Norton	99.5	78	9.57	.00028	3.45-3.18
			200	9.63	.00058	
			400	9.80	.00078	
			800	10.06	.00035	
			1200	10.37	.00049	
			1600	10.71	.00099	
			2000	11.06	.00290	
			2400	11.35	.01000	
29	Norton	99.5	78	9.30		8.5
			200	9.42		
			400	9.55		
			800	9.62		
			1200	9.70		
			1600	9.75	.00050 or less	
			2000	9.82	.00300	
			2400	9.95	.02700	
30	Silk City SC98D	98.0	78	8.44	.00120	40
			200	8.50	.00100	
			400	8.60	.00098	
			800	9.08	.00097	
			1200	9.58	.00220	
			1400	9.79	.00800	
31	Silk City SC85D	85.0	78	7.74	.00078	40
			200	7.72	.00070	
			400	7.72	.00065	
			800	7.94	.00200	
			1200	8.52	.01500	
			1400	8.90	.03000	
32	U.S. Stoneware 610	99.0	78	9.43	.00008	3.60-3.29
			200	9.50	.00015	
			400	9.66	.00025	
			800	9.96	.00030	
			1200	10.30	.00050	
			1600	10.62	.00140	
			2000	11.30	.00425	
			2200	11.27	.00790	

Item No.	Trade Designation	% Main Constituent	Temp °F	Dielectric Constant	Loss Tangent	Freq Gc
33	U.S. Stoneware A312	96.0+	78	8.47	.00080	3.81-3.65
			200	8.50	.00090	
			400	8.62	.00130	
			800	8.85	.00300	
			1200	9.20	.00875	
34	U.S. Stoneware A212	96.0	78	8.65	.00054	3.77-3.40
			200	8.70	.00058	
			400	8.81	.00070	
			800	9.06	.00125	
			1200	9.40	.00325	
			1400		.00510	
			1600	9.78	.00400	
			1800		.00265	
			2000	10.20	.00378	
			2200	10.48	.00700	
35	U.S. Stoneware A216	85.0	78	8.38	.00202	3.83-3.66
			200	8.45	.00214	
			400	8.60	.00235	
			800	8.85	.00305	
			1200	9.18	.00850	
36	U.S. Stoneware AL-STD	-	78	8.98	.00047	3.37-3.05
			200	9.04	.00052	
			400	9.16	.00080	
			800	9.42	.00135	
			1200	9.76	.00250	
			1600	10.14	.00525	
			1800	10.38	.01100	
37	Wesgo AL1009	99.85	78	9.5	.00009	3.55-3.25
			200	9.57	.00011	
			400	9.7	.00020	
			800	9.93	.00035	
			1200	10.2	.00070	
			1600	10.5	.00150	
			2000	10.88	.00270	
			2400	11.28	.00550	
38	Wesgo AL995	99.5	78	9.37	.00021	3.57-3.31
			200	9.41	.00022	
			400	9.56	.00025	
			800	9.8	.00035	
			1200	10.12	.00070	
			1600	10.35	.00135	
			2000	10.84	.00285	
			2300	11.22	.00794	

Item No.	Trade Designation	% Main Constituent	Temp °F	Dielectric Constant	Loss Tangent	Freq Gc
39	Wesgo AL995	99.5	78	9.46	.00021	9.375
			200	9.52	.00022	
			400	9.64	.00023	
			800	9.88	.00027	
			1200	10.15	.00039	
			1600	10.42	.00080	
			2000	10.73	.00250	
			2400	11.60	.00940	
40	Wesgo AL995	99.5	78	8.80	.00050	9.375
			500	8.98	.00085	
			1000	9.31	.00175	
			1200	9.47	.00395	
41	Wesgo AL300	97.6	78	9.46	.00050	3.53-3.19
			200	9.52	.00050	
			400	9.66	.00051	
			800	9.92	.00065	
			1200	10.27	.00095	
			1600	10.65	.00170	
			2000	11.6	.00850	
42	Wesgo AL300	97.6	78	8.30	.00056	9.375
			500	8.48	.00076	
			1000	8.76	.00096	
			1200	8.88	.00123	
43	Wesgo AL400	95.0	78	9.19	.00072	3.61-3.34
			200	9.25	.00074	
			400	9.39	.00077	
			800	9.62	.00090	
			1200	9.94	.00140	
			1600	10.17	.00300	
			1800	10.59	.00600	
44	Miscellaneous	99.9	78	9.60	.00049	8.5
			200	9.70	.00052	
			400	9.80	.00063	
			800	10.04	.00110	
			1200	10.25	.00450	

Item No.	Trade Designation	% Main Constituent	Temp °F	Dielectric Constant	Loss Tangent	Freq Gc
45	Miscellaneous	99.0	78	8.43		8.5
			200	8.48		
			400	8.57		
			800	8.74		
			1200	8.91	.00050 or less	
			1600	9.08	.00090	
			2000	9.25	.00630	
			2400	9.37	.01730	
46	Miscellaneous	99.0	78	8.90		8.5
			200	8.95		
			400	9.05		
			800	9.25		
			1200	9.45		
			1600	9.60	.00050 or less	
			2000	9.80	.00350	
			2400	10.00	.01400	
47	Miscellaneous	96.0	78	8.43		8.5
			200	8.50		
			400	8.61		
			800	8.78		
			1200	8.93	.00050 or less	
			1600	9.08	.00170	
			2000	9.24	.00670	
			2400	9.29	.01500	
48	Miscellaneous	94.0	78	8.26		8.5
			200	8.28		
			400	8.30		
			800	8.45		
			1200	8.70	.00050 or less	
			1600	9.00	.00250	
			2000	9.30	.01500	
			2400	9.72	.06000	

DIELECTRIC CONSTANT & LOSS TANGENT
BERYLLIA

Item No.	Trade Designation	% Main Constituent	Temp °F	Dielectric Constant	Loss Tangent	Freq Gc
49	American Lava 754	99.5	78	6.07	.00010	10
			400	6.11	.00010	
			800	6.22	.00010	
			1200	6.39	.00014	
			1400	6.49	.00029	
50	American Lava 754	99.5	78	5.99	.00320	25
			400	6.03	.00396	
			800	6.18	.00490	
			1200	6.42	.00580	
			1400	6.59	.00630	
51	American Lava 735	98.0	78	6.04	.00010	10
			400	6.04	.00010	
			800	6.13	.00010	
			1200	6.32	.00017	
			1400	6.41	.00038	
52	American Lava 735	98.0	78	6.07	.00450	25
			400	6.12	.00500	
			800	6.22	.00520	
			1200	6.42	.00560	
			1400	6.63	.00640	
53	Atomics Int'l	99.0	78	7.25	.00049	9.375
			200	7.29	.00048	
			400	7.38	.00046	
			800	7.60	.00045	
			1200	7.90	.00046	
			1600	8.23	.00050	
			2000	8.61	.00060	
			2400	9.09	.00105	
			2600	9.42	.00210	
54	Beryllium Corp. Berylco	99.7	78	6.44	.00252	9.375
			500	6.63	.00150	
			1000	6.89	.00215	
			1200	6.88	.00530	

Item No.	Trade Designation	% Main Constituent	Temp °F	Dielectric Constant	Loss Tangent	Freq Gc
55	Brush Beryllium F-1-7	99.5	Ambient	6.47	.0014	10
			600	6.95	.0019	
			1200	7.26	.0019	
			1600	7.72	.0019	
			2200	8.36	.0062	
			2600	8.75	.0023	
			3000	9.21	.0103	
56	Brush Beryllium B-6-11	99.0	Ambient	6.13	.0011	10
			600	6.26	.0011	
			1200	6.57	.0016	
			1600	6.76	.0026	
			2200	8.08	.0448	
			2600	7.80	.0252	
			3000	8.49	.0338	
57	Brush Beryllium B-7	-	78	6.66	.00150	10
			400	6.83	.00172	
			800	7.06	.00185	
			1200	7.30	.00190	
			1600	7.70	.00230	
			2000	8.07	.00400	
			2400	8.60	.00800	
			2600	8.96	.00960	
58	Brush Beryllium F-1-10	-	Ambient	6.28	.0010	10
			600	6.40	.0012	
			1200	6.70	.0020	
			1600	6.97	.0011	
			2200	7.85	.0072	
			2600	8.36	.0004	
			3000	8.74	.0027	
59	Brush Beryllium F-1-7	99.5	78	6.80	.00032	4.23-3.75
			200	6.82	.00032	
			400	6.92	.00033	
			800	7.13	.00035	
			1200	7.81	.00120	
			1600	7.96	.00270	
			1800	8.05	.00383	
			1900	-	.00386	
			2000	8.14	.00350	
			2400	8.54	.00750	
			2600	8.82	.01000	

Item No.	Trade Designation	% Main Constituent	Temp °F	Dielectric Constant	Loss Tangent	Freq Gc
60	Brush Beryllium B-6	98.5	78	6.64	.00083	4.45-4.04
			200	6.7	.00080	
			400	6.84	.00075	
			800	7.06	.00075	
			1200	7.4	.00115	
			1600	7.68	.00245	
			1800	8.04	.00400	
61	Brush Beryllium B-7-6	-	78	6.48	.00050	4.53-3.92
			200	6.53	.00051	
			400	6.67	.00065	
			800	6.94	.00110	
			1200	7.31	.00180	
			1600	7.69	.00265	
			2000	8.15	.00400	
			2400	8.73	.00930	
62	Brush Beryllium B-7-37	-	78	6.76	.00036	4.23-3.57
			200	6.79	.00035	3.58-3.27
			400	6.91	.00036	
			800	7.15	.00049	
			1200	7.44	.00095	
			1600	7.75	.00175	
			2000	8.14	.00300	
			2400	8.62	.01000	
63	Coors BD-98	98.0	78	6.88	.00047	9.375
			200	6.91	.00048	
			400	6.99	.00050	
			800	7.18	.00053	
			1200	7.43	.00060	
			1600	7.70	.00107	
			2000	8.03	.00265	
			2400	8.40	.00820	
64	Coors B-932	-	78	6.82	.00052	9.375
			200	6.85	53	
			400	6.93	54	
			800	7.15	67	
			1200	7.43	93	
			1600	7.74	.00143	
			2000	8.06	240	
			2400	8.39	455	

Item No.	Trade Designation	% Main Constituent	Temp. °F	Dielectric Constant	Loss Tangent	Freq Gc
65	National Beryllia Berloy	99.0	78	6.60	.00054	9.375
			200	6.66	.00055	
			400	6.75	.00056	
			800	6.95	.00058	
			1200	7.20	.00061	
			1600	7.47	.00068	
			2000	7.79	.00080	
			2400	8.11	.00130	
66	National Beryllia	-	78	6.59	.00044	3.87-3.14
		Note: Cold	200	6.60	.00042	
		Pressed &	400	6.72	.00040	
		Sintered-	800	6.96	.00050	
		High Purity	1200	7.29	.00100	
		Beryllia	1600	7.65	.00180	
			2000	8.15	.00350	
			2200	8.52	.01040	
67	Miscellaneous	99.5				
		Hot Pressed	78	6.20		8.5
			200	6.25		
			400	6.32	.00100	
			800	6.45	.00120	
			1200	6.70	.00220	
			1600	6.85	.00280	
			2000	7.25	.01050	
			2200	7.50	.03900	

DIELECTRIC CONSTANT & LOSS TANGENT
BORON NITRIDE

Item No.	Trade Designation	% Main Constituent	Temp °F	Dielectric Constant	Loss Tangent	Freq Gc
68	Carborundum	-	78			8.5
			200			
			400	4.55		
			800	4.45	.00060	
			1200	4.42	.00140	
			1600	4.50	.00370	
			2000	4.68	.00950	
			2200	4.80	.01360	
69	Carborundum	-				
		Electric	78	4.400	.00012	9.375
		field perpen-	200	4.405	.00012	
		dicular to	400	4.413	.00013	
		molding pre-	800	4.430	.00018	
		ssure	1200	4.455	.00030	
			1600	4.492	.00083	
			1800	4.525	.00175	
70	Carborundum	-	78	4.777	.00033	5.08-4.99
			200	4.780	.00033	
			400	4.788	.00034	
			800	4.802	.00040	
			1200	4.826	.00090	
			1600	4.850	.00140	
			2000	4.878	.00540	
71		-	78	5.120	.00014	4.83-4.77
		Electric	200	5.120	.00010	
		field par-	400	5.120	.00008	
		allel to	800	5.123	.00008	
		deposition	1200	5.135	.00014	
		field	1600	5.160	.00016	
			2000	5.193	<.00005	
			2400	5.233	.00028	

DIELECTRIC CONSTANT & LOSS TANGENT
PYROCERAM

Item No.	Trade Designation		% Main Constituent	Temp °F	Dielectric Constant	Loss Tangent	Freq Gc
72	Corning	9606	--------	78	5.810	.00031	4.58-4.48
				200	5.826	.00033	
				400	5.862	.00049	
				800	5.923	.00140	
				1200	5.997	.00370	
				1400	6.040	.00570	
73	Corning	9606	--------	78	5.65	.00019	9.375
				200	5.67	.00021	
				400	5.72	.00031	
				800	5.79	.00095	
				1200	5.84	.00360	
				1600	5.90	.01040	
				2000	5.97	.01380	
74	Corning	9606	--------	78	5.63		9.4
				200	5.63		
				400	5.63		
				800	5.65		
				1200	5.72		
				1600	5.79		
				2000	6.03		
75	Corning	9606	--------	75	5.5	.00030	10
				1500	5.7	.00150	
				2000			
76	Corning	9608	--------	78	6.54	.0068	10
				200	6.55	80	
				400	6.60	.0101	
				800	6.70	.0250	

DIELECTRIC CONSTANT & LOSS TANGENT
SILICATES

Item No.	Trade Designation	% Main Constituent	Temp °F	Dielectric Constant	Loss Tangent	Freq Gc
77	American Optical-Amersil	-------- Commercial	400	3.940		10
			800	3.930	.00040	
			1200	3.925	.00050	
			1600	3.920	.00075	
			2000	3.910	.00230	
			2400	3.900	.00480	
78	American Optical-Amersil	-------- Translucent	78	3.710	.00027	5.50-5.35
			200	3.721	.00026	
			400	3.745	.00024	
			800	3.782	.00030	
			1200	3.824	.00055	
			1600	3.866	.00120	
			2000	3.910	.00400	
79	American Optical-Amersil	-------- Clear	78	3.818	.00015	5.50-5.37
			200	3.822	.00014	
			400	3.836	.00010	
			800	3.861	.00008	
			1200	3.890	.00005	
			1600	3.918	.00025	
			2000	3.948	.00090	
			2400	3.975	.00165	
80	Corning 7900	96.0	78	3.80	.00065	10
			200	3.78	.00072	
			400	3.77	.00085	
			800	3.77	.00148	
			1000	3.77	.00195	
81	Corning 7941	-------- Some Sintering	78	3.380	.00050	5.90-5.76
			200	3.388	.00052	
			400	3.410	.00065	
			800	3.442	.00080	
			1200	3.484	.00140	
			1600	3.524	.00260	
			2000	3.566	.00480	
82	Corning 7940M	--------	78	3.400	.00040	9.375
			200	3.410	.00038	
			400	3.427	.00040	
			800	3.459	.00064	
			1200	3.486	.00130	
			1600	3.509	.00230	
			1800	3.521	.00285	

Item No.	Trade Designation	% Main Constituent	Temp °F	Dielectric Constant	Loss Tangent	Freq Gc
83	Corning 915C	--------	78	3.84	.00010	9.375
			200	3.851		
			400	3.867		
			800	3.897		
			1200	3.923		
			1400	3.931	.00010	
			1600	3.935	.00011	
			1800	3.932	.00104	
84	Corning	---------	78	3.73	.00005	10
			200	3.75	.00009	
			400	3.77	.00019	
			800	3.79	.00024	
			1200	3.81	.00015	
			1600	3.84	.00011	
			2000	3.88	.00020	
			2400	3.94	.00020	
			2600	3.98	.00024	
85	Georgia Tech A-694-12	Pure Silica Glazed 20 sec.	Ambient	3.35	.0023	10
			500	3.33	.0018	
			1000	3.33	.0024	
			1500	3.33	.0036	
			2000	3.39	.0055	
			2500	3.57	.0090	
86	Georgia Tech A-694-13	Pure Silica Hand glazed	Ambient	3.37	.0031	
			500	3.31	.0017	
			1000	3.28	.0024	
			1500	3.30	.0033	
			2000	3.46	.0061	
			2500	3.61	.0092	
87	Georgia Tech A-694-1	-------- Cr_2O_3 added to slip before casting	Ambient	3.13	.0030	9.375
			500	3.19	.0035	
			1000	3.16	.0067	
			1500	3.28	.0144	
			2000	3.32	.0165	
88	Georgia Tech A-694-2	-------- N:O added to slip before cast	Ambient	3.17	.0028	9.375
			500	3.25	.0026	
			1000	3.28	.0033	
			1500	3.30	.0070	
			2000	3.35	.0134	

Item No.	Trade Designation	% Main Constituent	Temp °F	Dielectric Constant	Loss Tangent	Freq Gc
89	Georgia Tech A-694-3	-------- Cast from pure Silica, then impregnated with Cr_2O_3	Ambient	3.14	.0030	9.375
			500	3.14	.0057	
			1000	3.22	.0162	
			1500	3.26	.0231	
			2000	3.31	.0279	
90	Georgia Tech A-694-6	-------- Cr_2O_3 adde to slip before casting. Unglazed	Ambient	3.40	.0028	9.375
			500	3.39	.0047	
			1000	3.44	.0198	
			1500	3.60	.0211	
			2000	3.72	.0650	
			2500	4.13	.1209	
91	Georgia Tech A-694-7	-------- Cr_2O_3 added to slip before casting Glazed 10 sec	Ambient	3.27	.0022	9.375
			500	3.27	.0025	
			1000	3.35	.0103	
			1500	3.44	.0145	
			2000	3.53	.0186	
			2500	3.69	.0294	
92	Georgia Tech A-694-8	-------- Cr_2O_3 added to slip before casting Glazed 20sec	Ambient	3.33	.0030	9.375
			500	3.34	.0036	
			1000	3.39	.0110	
			1500	3.45	.0150	
			2000	3.48	.0189	
			2500	3.68	.0263	
93	Georgia Tech A-694-9	-------- Cr_2O_3 added to slip before casting Glazed 30sec	Ambient	3.33	.0025	9.375
			500	3.30	.0031	
			1000	3.34	.0093	
			1500	3.39	.0138	
			2000	3.44	.0171	
			2500	3.63	.0227	
94	Georgia Tech A-964-10	-------- Cr_2O_3 added to slip before casting Hand glazed 1 min till smooth	Ambient	3.48	.0007	9.375
			500	3.50	.0042	
			1000	3.54	.0211	
			1500	3.65	.0477	
			2000	3.76	.0802	
			2500	4.30	.1371	
95	Georgia Tech A-694-11	Pure Silica Unglazed	Ambient	3.38	.0008	9.375
			500	3.39	.0013	
			1000	3.38	.0030	
			1500	3.47	.0044	
			2000	3.44	.0068	
			2500	3.63	.0111	

Item No.	Trade Designation	% Main Constituent	Temp °F	Dielectric Constant	Loss Tangent	Freq Gc
96	General Electric 101	--------	78	3.847	.00010	6.10-5.97
			200	3.850	.00010	
			400	3.858	.00011	
			800	3.870	.00013	
			1200	3.882	.00025	
			1600	3.903	.00070	
			1800	3.914	.00175	
			2000	3.933	.00590	
97	Miscellaneous	--------	78	3.73	.00200	
			200	3.73	.00127	
			400	3.73	.00125	
			800	3.73	.00210	
			1200	3.73	.00437	
			1600	3.75	.00795	
			2000	4.18	.01020	
			2400	4.68	.01070	
98	Miscellaneous	--------	75	3.17	.0002	
			1500	3.18	.0006	
			2000	3.28	.0070	
			2500	3.42	.0120	

DIELECTRIC CONSTANT LOSS TANGENT
MAGNESIA

Item No.	Trade Designation	% Main Constituent	Temp °F	Dielectric Constant	Loss Tangent	Freq Gc
99	Minn.-Honeywell	-	78	9.65	.00015	3.38-3.02
			200	9.70	.00010	
			400	9.77	<.00005	
			800	9.96	<.00005	
			1200	10.26	<.00005	
			2000	11.05	.00048	
			2400	11.55	.00165	
			2800	12.10	.00900	
100	BAC	—	78	9.50		9.375
		Loss tangent	200	9.58		
		less than	400	9.77		
		.0001 from	800	10.08		
		10°F to	1200	10.39		
		1850°F	1600	10.67		
			1800	10.81	<.0001	

DIELECTRIC CONSTANT & LOSS TANGENT
SPINEL

Item No.	Trade Designation	% Main Constituent	Temp °F	Dielectric Constant	Loss Tangent	Freq Gc
101	BAC	----	78	8.25		9.375
			200	8.30	.00015	
			400	8.41	.00016	
			800	8.70	.00023	
			1200	9.07	.00037	
			1600	9.50	.00080	
			2000	10.00	.00265	
			2400	10.57	.01020	

SILICATES MISC.

Item No.	Trade Designation	% Main Constituent	Temp °F	Dielectric Constant	Loss Tangent	Freq Gc
102	Steatit-Magnesia Frequenta M	AG ----	78	6.685	.00048	4.08-3.86
			200	6.730	.00046	
			400	6.830	.00048	
			800	7.020	.00065	
			1200	7.250	.00110	
			1400	7.350	.00150	

ADHESIVES

Item No.	Trade Designation	% Main Constituent	Temp °F	Dielectric Constant	Loss Tangent	Freq Gc
103	Interpace	----	78	5.47	.02120	9.375
			500	6.03	.04180	
			1000	6.73	.13280	
			1200	6.66	.26570	
104	Narmcad 110	----	78	5.86	.01540	9.375
			500	6.21	.03460	
			1000	6.79	.08150	
			1200	6.93	.23500	
105	Narmcad 120	----	78	6.17	.01350	9.375
			500	6.49	.02690	
			1000	7.14	.07040	
			1200	7.16	.26460	
106	Pycard 500	----	78	6.10	.00490	9.375
			500	6.05	.00590	
			1000	6.12	.00790	
			1200	6.26	.01220	
107	Pyroceram 45	----	78	5.23	.00390	9.375
			500	5.31	.00410	
			1000	5.57	.00330	
			1200	5.73	.00340	

VOLUME RESISTIVITY
ALUMINA

Item No.	Trade Designation	% Main Constituent	Temp °C	Resistivity Ohm-cm
108	American Lava 748	98.0	25	$> 10^{14}$
			100	$> 10^{14}$
			300	$> 10^{14}$
			500	3.3×10^{11}
			700	3.0×10^{9}
			900	7.1×10^{7}
109	American Lava 614	96.0	25	$> 10^{14}$
			100	2.0×10^{13}
			300	1.1×10^{10}
			500	7.3×10^{7}
			700	3.5×10^{6}
			900	6.8×10^{5}
110	American Lava 719	94.0	25	$> 10^{14}$
			100	$> 10^{14}$
			300	6.0×10^{12}
			500	1.4×10^{11}
			700	9.7×10^{8}
			900	3.2×10^{7}
111	American Lava 576	85.0	25	$> 10^{14}$
			100	2.0×10^{13}
			300	5.0×10^{10}
			500	1.0×10^{8}
			700	3.0×10^{6}
			900	4.0×10^{5}
112	Coors AD99	99.0	25	$> 10^{14}$
			300	1.0×10^{13}
			500	6.3×10^{10}
			700	5.0×10^{8}
			1000	2.0×10^{6}
113	Coors AD96	96.0	25	$> 10^{14}$
			300	3.1×10^{11}
			500	4.0×10^{9}
			700	1.0×10^{8}
			1000	1.0×10^{6}

Item No.	Trade Designation	% Main Constituent	Temp °C	Resistivity Ohm-cm
114	Coors AD94	94.0	25	$>10^{14}$
			300	9.0×10^{11}
			500	2.5×10^{9}
			700	5.0×10^{7}
			1000	5.0×10^{5}
115	Coors AD85	85.0	25	$>10^{14}$
			300	4.6×10^{10}
			500	4.0×10^{8}
			700	7.0×10^{6}
116	Diamonite P-3142-1	95-97	250	2×10^{14}
			500	1.2×10^{10}
117	Diamonite B-890-2	90-95	250	6×10^{13}
			500	6×10^{10}
118	Diamonite P-3662	85-90	250	4.9×10^{10}
			500	1.0×10^{8}
119	Silk City SC98D	98.0	200	$>10^{13}$
			300	7.4×10^{12}
			400	2.8×10^{12}
			500	2.5×10^{11}
			600	7.0×10^{8}
			700	3.2×10^{7}
			800	3.1×10^{6}
			900	5.2×10^{5}
			1000	1.4×10^{5}
			1100	5.0×10^{4}
			1200	1.6×10^{4}
			1300	5.5×10^{3}
			1400	$< 10^{3}$
120	WESGO AL1009	99.85	25	$>10^{14}$
			300	7.0×10^{11}
			600	1.2×10^{10}
			900	1.6×10^{8}
121	WESGO AL995	99.5	25	$>10^{14}$
			300	2.0×10^{11}
			600	6.0×10^{8}
			900	2.5×10^{6}

Item No.	Trade Designation	% Main Constituent	Temp °C	Resistivity Ohm-cm
122	WESGO AL300	97.6	25	$> 10^{14}$
			300	1.0×10^{12}
			600	2.3×10^{10}
			900	5.0×10^{8}
123	WESGO AL400	95.0	25	$> 10^{14}$
			300	4.0×10^{13}
			600	2.4×10^{10}
			900	1.7×10^{7}
124	Miscellaneous	99.9	600	1×10^{11}
			700	7×10^{9}
			800	5×10^{8}
			900	6×10^{7}
			1000	8×10^{6}
			1100	1×10^{6}
			1200	6×10^{5}
			1300	1×10^{5}
			1400	9×10^{4}
	BERYLLIA			
125	American Lava 754	99.5	25	$> 10^{14}$
			100	$> 10^{14}$
			300	$> 10^{14}$
			500	1.0×10^{13}
			700	1.0×10^{11}
			900	3.0×10^{9}
126	Coors BD995	99.5	500	$> 10^{13}$
			600	1.6×10^{12}
			700	1.1×10^{10}
			800	1.7×10^{9}
			900	2.4×10^{8}
			1000	6.1×10^{7}
			1100	1.1×10^{7}
			1200	1.7×10^{6}
			1300	3.9×10^{5}
			1400	5.1×10^{4}
			1500	7.6×10^{3}
			1600	1.9×10^{3}

Item No.	Trade Designation	% Main Constituent	Temp °C	Resistivity Ohm-cm
127	Coors BD99	99.0	500	$> 10^{13}$
			600	2.4×10^{12}
			700	1.9×10^{11}
			800	1.4×10^{10}
			900	1.6×10^{9}
			1000	2.8×10^{8}
			1100	4.3×10^{7}
			1200	4.9×10^{6}
			1300	6.4×10^{5}
			1400	1.3×10^{5}
			1500	3.0×10^{4}
			1600	4.0×10^{3}
128	Coors BD98	98.0	500	$> 10^{13}$
			600	1.2×10^{12}
			700	3.2×10^{10}
			800	2.1×10^{9}
			900	3.5×10^{8}
			1000	7.7×10^{7}
			1100	1.7×10^{7}
			1200	1.2×10^{6}
			1300	1.6×10^{5}
			1400	2.8×10^{4}
			1500	4.3×10^{3}
			1600	$< 10^{3}$
129	Coors BD96	96.0	500	1.0×10^{13}
			600	3.5×10^{11}
			700	2.1×10^{10}
			800	1.9×10^{9}
			900	2.1×10^{8}
			1000	4.6×10^{7}
			1100	9.0×10^{6}
			1200	4.6×10^{5}
			1300	5.3×10^{4}
			1400	4.3×10^{3}
			1500	$< 10^{3}$
130	Miscellaneous	----	1000	8×10^{7}
			1100	1×10^{7}
			1200	7×10^{6}
			1300	8×10^{5}
			1400	2×10^{5}
			1500	8×10^{4}
			1600	4×10^{4}
			1700	1×10^{4}
			1800	9×10^{3}
			1900	4×10^{3}
			2000	1×10^{3}

VOLUME RESISTIVITY
SILICAS

Item No.	Trade Designation	% Main Constituent	Temp °C	Resistivity Ohm-cm
131	Corning 7900	-	250	7×10^9
132	Corning 7900M	-	100	5×10^{16}
			150	8×10^{14}
			200	3×10^{13}
			250	2.5×10^{12}
			300	3×10^{11}
			350	3×10^{10}
			400	7×10^9
			450	1×10^9

SPINEL

Item No.	Trade Designation	%Main Constituent	Temp °C	Resistivity Ohm-cm
133	--------	----	500	2×10^7
			600	9×10^6
			700	3×10^6
			800	10^6
			900	6×10^5
			1000	2.5×10^5
			1100	10^5

PYROCERAM

Item No.	Trade Designation	%Main Constituent	Temp °C	Resistivity Ohm-cm
134	Corning 9606	----	50	3×10^{15}
			100	5×10^{13}
			150	1×10^{12}
			200	8×10^{10}
			250	1×10^{10}
			300	3×10^9
			350	7×10^8
			400	1×10^8
			450	3×10^7
135	Corning 9608	----	250	10^8

BORON NITRIDE

Item No.	Trade Designation	%Main Constituent	Temp °C	Resistivity Ohm-cm
136	Carborundum Co.	----	27	2×10^{13}
			500	4×10^{10}
			1000	5×10^4
			1500	8×10^2

137 MAGNESIA

Item No.	Trade Designation	%Main Constituent	Temp °C	Resistivity Ohm-cm
137	--------	----	300	10^{15}
			400	5×10^{13}
			500	2×10^{12}
			600	1×10^{11}
			700	10^{10}
			800	10^9
			900	10^8
			1000	1×10^7
			1100	3×10^6
			1200	10^6
			1300	2×10^5

Item No.	Trade Designation	% Main Constituent	Temp oC	Resistivity Ohm-cm
137			1400	8×10^4
			1500	2×10^4
			1600	10^4
			1700	4×10^3
			1800	1×10^3
			1900	9×10^2
			2000	5×10^2
			2100	1×10^2
			2200	10^2
	SILICATES			
138	--------	----	300	3×10^{13}
			400	8×10^{11}
			500	2.5×10^{10}
139	--------	----	200	1.5×10^{14}
			250	5×10^{13}
			300	9×10^{12}
			350	1.5×10^{12}
			400	5×10^{11}
			450	8×10^{10}
140	--------	----	200	2×10^{13}
			250	3×10^{12}
			300	3×10^{11}
			350	5×10^{10}
			400	8×10^9
			450	1×10^9
141	--------	----	300	7×10^9
			400	1.5×10^8
			500	1.0×10^7

DIELECTRIC STRENGTH
ALUMINA

Item No.	Trade Designation	% Main Constituent	Temp °C	Dielectric Strength Volt/Mil
142	Coors AD99	99.0	25°C	220-240 (1/4" sample in oil)
143	Coors AD96	96.0	25°C	220-240 (1/4" sample in oil)
144	Diamonite P-3142-1	95-97	Ambient	275 (1/8" sample)
145	Diamonite B-890-2	90-95	Ambient	230 (1/8" sample)
146	Diamonite P-3662	85-90	Ambient	210-220 (1/8" sample)
147	Wesgo AL 995	99.5	Ambient	800 (.100" sample in oil).
148	Wesgo AL 300	97.6	Ambient	1100 (.100" sample in oil)
149	Wesgo AL 400	95.0	Ambient	700 (.100" sample in oil)

DIELECTRIC STRENGTH
BERYLLIA

Item No.	Trade Designation	% Main Constituent	Temp °C	Dielectric Strength Volt/Mil
150	Brush Beryllium	----	25	470
			65	463
			100	435
			200	425
151	Coors BD98	98.0	Ambient	238 (¼" sample in oil)
			Ambient	339 (1/8" sample in oil)
152	Coors BD96	96.0	Ambient	251 (¼" sample in oil)
			Ambient	351 (¼" sample in oil)
153	National Beryllia Berlox	99.0	Ambient	> 300

SPECIFIC HEAT
ALUMINA

Item No.	Trade Designation	% Main Constituent	Temp. °C	Specific Heat Cal/Gm °C
154	-	99.97-99.98	0	.1731
			20	.1830
			40	.1922
			60	.2007
			80	.2085
			100	.2157
			120	.2224
			140	.2285
			160	.2341
			180	.2392
			200	.2438
			220	.2480
			240	.2518
			260	.2552
			280	.2583
			300	.2611
			320	.2637
			340	.2660
			360	.2681
			380	.2701
			400	.2719
			420	.2736
			440	.2753
			460	.2769
			480	.2784
			500	.2799
			520	.2813
			540	.2867
			560	.2840
			580	.2853
			600	.2865
			620	.2877
			640	.2888
			660	.2899
			680	.2909
			700	.2919
			720	.2928
			740	.2937
			760	.2945
			780	.2953
			800	.2960
			820	.2967
			840	.2974
			860	.2981
			880	.2988
			900	.2995

Item No.	Trade Designation	% Main Constituent	Temp. °C	Specific Heat Cal/Gm °C
155	Coors	99.5	100	.24
			400	.27
			700	.30
			900	.31
			1100	.28
			1300	.25
			1375	.25
156	Interpace	99.5	100	.27
			400	.25
			700	.25
			900	.28
			1100	.28
			1300	.28
			1375	.28
157	Norton	99.5	100	.27
			400	.29
			700	.26
			900	.28
			1100	.28
			1300	.28
			1375	.28
158	Coors AD99	99.0	24	.230
			260	.256
			538	.285
			816	.300
			1093	.280
			1371	.250

BERYLLIA

Item No.	Trade Designation	% Main Constituent	Temp. °C	Specific Heat Cal/Gm °C
159	Coors	100	26	.245
			260	.382
			538	.450
			816	.500*

*Extrapolated

Item No.	Trade Designation	% Main Constituent	Temp. °C	Specific Heat Cal/Gm °C
160	Coors BD-98	98	100	.31
161	Coors BD-96	96	100	.31
162	Unknown		66	.200 - .235
			260	.325 - .375
			538	.425 - .475
			816	.475 - .525
			1093	.485 - .550
			1371	.500 - .555
			1538	.512 - .565
			1649	.525 - .575
			2038	.550 - .685
			2204	.560 -
			2760	.600 -
		FUSED SILICA		
163	Corning 7940	-	200	.230
			400	.260
			600	.270
			800	.285
			1000	.290
			1200	.305
			1350	.320
164	Corning 7941	-	25	.179
			100	.205
			200	.229
			300	.245
			400	.257
			500	.266
			600	.273
			700	.280
			800	.286
			900	.290
			1000	.295
			1100	.299
165	Corning 7900		25	.182
			100	.206
			200	.230
			300	.244
			400	.258
			500	.271
			600	.281
			700	.290
			800	.300

PYROCERAM

Item No.	Trade Designation	% Main Constituent	Temp. °C	Specific Heat Cal/Gm °C
166	Corning 9606	-	25	.180
			100	.210
			200	.231
			300	.245
			400	.256
			500	.268
			600	.275
			700	.284
			800	.292
			900	.301
			1000	.311
167	Corning 9608	-	25	.192
			100	.215
			200	.240
			300	.258
			400	.271
			500	.282
			600	.292
			700	.302
			800	.312

THERMAL CONDUCTIVITY
ALUMINA

Item No.	Trade Designation	% Main Constituent	Temp °C	Thermal Conductivity Cal/Cm Sec °C	
168	Coors AD 995	99.5	25	.069	
			300	.037	
169	Coors AD 995	99.5	24	----	
			149	.039	
			260	.030	
			538	.019	
			816	.011	
				Run #1	Run #2
170	Coors AD 995	99.5	100	.099	.100
			300	.022	.031
			500	.019	.024
			600	.019	.023
			800	.013	.014
			1000	.014	----
			1100	.016	.023
			1200	.017	.023
			1300	.018	.023
			1375	.020	.026
171	Coors AD 99	99	25	.069	
			300	.037	
172	Coors AD 94	94	25	.048	
			300	.024	
173	Coors AD 85	85	25	.032	
			300	.017	
174	Silk City 99P	99	73.7	5.54×10^{-2}	
			118.6	3.56	
			132.3	2.94	
			215.0	2.27	
			391.0	1.94	
			514.4	1.57	
			634.1	1.33	
			746.8	1.14	
			874.9	1.02	
			932.1	.98	
			936.2	.98	
			938.2	.98	
			1036.1	.89	
			1054.2	.86	
			1078.6	.84	
			1079.7	.87	
			1359.0	.80	

Item No.	Trade Designation	% Main Constituent	Temp °C	Thermal Conductivity Cal/Cm Sec °C
175	Silk City 98D	98	55.0	7.1 x 10^{-2}
			61.0	6.2
			161.0	4.2
			186.0	3.8
			411.0	1.4
			1300.0	0.5
176	Silk City SC85D	85	40.0	6.90 x 10^{-2}
			240.0	4.75
			635.0	1.70
			680.0	1.75
			905.0	1.40
			1090.0	1.30
			1300.0	1.15

ALUMINA WITH ADDITIVES

Item No.	Trade Designation	% Main Constituent	Temp °C	Thermal Conductivity Cal/Cm Sec °C
177	--------	----	75	.092
		Polycrystalline	100	.080
		12.5% porosity	200	.057
			400	.032
			600	.022
			800	.017
			1000	.016
			1200	.015
178	--------	----	75	.092
		Polycrystalline	100	.080
		3.0% porosity	200	.057
			400	.032
			600	.022
			800	.017
			1000	.016
			1200	.015
179	--------	----	200	.062
		Polycrystalline	400	.037
		.25% porosity	600	.023
			800	.022
			1000	.022
180	--------	----	75	.044
		Polycrystalline	100	.041
		6.42% Cr_2O_3	200	.033
		by volume	400	.020
			600	.015
			800	.012
			1000	.011

Item No.	Trade Designation	% Main Constituent	Temp °C	Thermal Conductivity Cal/Cm Sec °C
181	--------	--------	75	.054
		Polycrystalline	100	.049
		2.88% Cr_2O_3	200	.040
		by volume	400	.025
			600	.017
			800	.015
			1000	.014
182	--------	--------	75	.057
		Polycrystalline	100	.055
		1.26% Cr_2O_3	200	.042
		by volume	400	.027
			600	.020
			800	.016
			1000	.015
183	--------	--------	200	.052
		Single crystal	400	.032
		1.10% Cr_2O_3	600	.022
		by volume	800	.021
184	--------	--------	75	.087
		Single crystal	100	.082
		.75% Cr_2O_3	200	.053
		by volume	400	.035
			600	.026
			800	.024
			1000	.025
			1200	.034
185	--------	---------	75	.074
		Polycrystalline	100	.062
		.247% Cr_2O_3	200	.053
		by volume	400	.030
			600	.020
			800	.017
			1000	.014
186	--------	--------	75	.095
		Single crystal	100	.090
		.16% Cr_2O_3	200	.062
		by volume		

SILICA

Item No.	Trade Designation	% Main Constituent	Temp °C	Thermal Conductivity Cal/Cm Sec °C
187	Corning 7900	--------	25	.00352
			100	.00379
			200	.00401
			300	.00419
			400	.00431
			500	.00440
			600	.00450
			700	.00459
			800	.00468
188	Corning 7940	--------	100	.0035
			200	.0039
			300	.0042
			400	.0046
			500	.0048
			600	.0050
			700	.0053
			800	.0054
			900	.0056
189	Corning 7941	--------	25	.00215
			100	.00225
			200	.00240
			300	.00255
			400	.00260
			500	.00261
			600	.00261
			700	.00261
			800	.00261
			900	.00261
190	--------	--------	100	.00128
		Slip Cast	200	.00132
			300	.00136
			400	.00140
			500	.00145
			600	.00153
			700	.00161
			800	.00169
			900	.00174
			1000	.00186
			1100	.00207

Item No.	Trade Designation	% Main Constituent	Temp °C	Thermal Conductivity Cal/Cm Sec °C
191	---------	--------	100	.00355
		Clear, Foamed	200	.00413
			300	.00487
			400	.00620
			500	.00810
		ALUMINA		
192	--------	--------	316	.038
		Sapphire,	371	.033
		Synthetic	427	.030
		100% Al_2O_3	482	.027
			538	.024
			593	.023
			816	.019
			927	.018
		PYROCERAM		
193	Corning 9606	--------	25	.00895
			100	.00865
			200	.00825
			300	.00800
			400	.00785
			500	.00758
			600	.00743
			700	.00730
			800	.00720
			900	.00710
194	Corning 9608	--------	25	.00485
			100	.00509
			200	.00529
			300	.00545
			400	.00555
			500	.00558
			600	.00557
			700	.00543
			800	.00537

Item No.	Trade Designation	% Main Constituent	Temp °C	Thermal Conductivity Cal/Cm Sec °C
195	Brush Beryllium	98.5	119	49.7
			238	26.2
			309	22.5
			558	12.3
			694	9.2
			841	5.4
			1040	4.5
			1295	3.9
196	Unknown	--------	100	50.0
		2.7 - 2.86 dense	200	39.8
			400	21.1
			600	10.7
			800	6.15
			1000	4.62
			1200	3.93
			1400	3.72
			1600	3.46
			1800	3.52
197	Unknown	---------	100	52.5
		3.01 dense	200	41.7
			400	22.2
			600	11.2
			800	6.45
			1000	4.85
			1200	4.12
			1400	3.91
			1600	3.62
			1800	3.69
198	Unknown	--------	30	51.5
		2.62 dense	50	47.0
			100	37.8
			150	31.7
			200	27.0
			250	23.2
			300	20.2
			350	17.8
			400	15.9
			450	14.3
			500	12.9
			550	11.9
			600	11.0
			650	10.3
			700	9.7
			746	9.2

THERMAL EXPANSION
ALUMINA

Item No.	Trade Designation	% Main Constituent	Temp. °C	Thermal Expansion Inch/Inch X10^{-4} Run #1	Run #2
199	Coors AD995	99.5	100	-	3.7
			200	13.4	-
			300	22.7	21.0
			500	36.5	40.8
			700	56.9	58.7
			900	71.7	73.8
			1000	80.5	72.4
			1100	88.0	89.7
			1200	96.0	97.6
			1300	102.4	106.7
			1375	109.4	112.5
				Inch/Inch X10^{-4}	
200	Coors AD995	99.5	100	3.29	3.34
			200	11.1	10.5
			300	18.4	18.0
			400	26.3	25.5
			500	30.3	30.2
			600	42.6	43.0
			700	51.1	52.4
			800	60.0	61.7
			900	70.6	72.9
			1000	83.9	83.0
			1100	95.6	95.1
			1200	106.4	106.2
			1300	117.2	116.7
			1375	125.5	126.0
				Inch/Inch °C X10^{-6}	
201	Coors AD995	99.5	21-260	6.8	
			260-538	8.3	
			538-982	9.2	
			21-982	8.33	

Item No.	Trade Designation	% Main Constituent	Temp °C	Thermal Expansion
				Inch/Inch X10^{-4}
202	Coors AD995	99.5	260	17.0
			538	40.0
			816	64.0
			982	80.0
			1093	91.0
			1204	102.0
				Inch/Inch °C X10^{-6}
203	Coors AD99	99.0	-151-21	2.7
			21-260	6.3
			260-538	8.1
			538-982	9.0
			21-982	8.12
				Inch/InchX10^{-4}
204	Coors AD99	99.0	260	15
			538	36
			816	60
			982	75
			1093	80
			1204	97
				Inch/Inch °C X10^{-6}
205	Coors AD96 Formerly El-95	96.0	-151-21	2.7
			21-260	6.7
			260-538	8.3
			538-982	9.0
			21-982	8.22
				Inch/Inch °C X10^{-6}
206	Coors AD94 Formerly Al-200	94.0	-151-21	3.1
			21-260	6.7
			260-538	7.6
			538-982	8.8
			21-982	7.91
				Inch/Inch °C X10^{-6}
207	Coors AD85 Formerly AB-2	85.0	-151-21	2.9
			21-260	5.9
			260-538	9.0
			538-982	8.8
			21-982	7.58

Item No.	Trade Designation	% Main Constituent	Temp. °C	Thermal Expansion Inch/Inch X10^{-4} Run # 1	Run # 2
208	Interpace	99.5	100	4.64	4.15
			300	21.55	21.6
			500	37.7	39.0
			700	53.4	54.9
			900	71.2	74.3
			1000	76.5	77.3
			1100	83.6	80.9
			1200	90.4	88.4
			1300	92.2	94.5
			1375	87.6	92.4
209	Interpace	99.5	100	3.5	3.7
			200	11.25	11.3
			300	19.72	19.1
			400	28.14	27.36
			500	32.65	32.34
			600	45.76	45.66
			700	56.12	55.34
			800	65.89	66.73
			900	76.38	75.97
			1000	82.44	84.73
			1100	91.55	94.94
			1200	102.16	105.44
			1300	112.35	114.28
			1375	121.60	119.16
210	Norton	99.5	100	3.7	3.7
			300	20.7	20.5
			500	36.8	39.3
			700	50.6	57.7
			900	69.1	71.7
			1000	77.3	81.0
			1100	88.9	88.1
			1200	96.6	99.9
			1300	105.3	108.4
			1375	111.3	115.7
211	Norton	99.5	100	3.50	3.34
			200	10.5	10.9
			300	18.4	18.6
			400	27.1	27.1
			500	31.3	31.4
			600	44.2	44.1
			700	53.1	53.0

Item No.	Trade Designation	% Main Constituent	Temp. °C	Thermal Expansion	
				Inch/Inch X10^{-4}	
				Run 1	Run 2
212	Norton	99.5	800	62.6	64.1
			900	74.8	74.4
			1000	84.6	84.0
			1100	94.4	93.5
			1200	103.9	102.9
			1300	113.3	112.8
			1375	116.9	117.9
				Inch/Inch °C X10^{-6}	
213	Wesgo Al-1009	99.85	25-200	6.9	
			200-400	8.5	
			400-600	9.0	
			600-800	9.8	
			800-1000	13.0	
214	Wesgo Al-995	99.5	25-200	6.9	
			200-400	8.5	
			400-600	9.0	
			600-800	9.8	
			800-1000	13.0	
215	Wesgo Al-300	97.6	25-200	8.5	
			200-400	8.5	
			400-600	9.0	
			600-800	8.3	
			800-1000	12.5	
216	Wesgo Al-400	95.0	25-200	8.0	
			200-400	8.0	
			400-600	8.5	
			600-800	9.5	
			800-1000	12.5	

BERYLLIA

Item No.	Trade Designation	% Main Constituent	Temp. °C	Thermal Expansion Inch/Inch X10^{-4}
217	Coors	100	26	0
			260	14.0
			538	40.0
			816	72.0
			982	92.0
218	Coors BD-98	98	25-1000	9.44×10^{-6}
219	Coors BD-96	96	25-1000	9.3×10^{-6}
220	Unknown	—	25	0
		Fired to 18 cone.	50	1.23
			100	4.09
			150	7.2
			200	10.7
			250	14.5
			300	18.3
			350	22.4
			400	27.0
			450	30.9
			500	35.2
			550	40.0
			600	45.0
			650	49.7
			700	54.9
			750	59.9
			800	65.3
			850	70.8
			900	75.7
			950	81.1
			1000	86.7

Item No.	Trade Designation	% Main Constituent	Temp. °C	Thermal Expansion Inch/Inch X10^{-4} Run #1	Run #2
221	Unknown	—	25	0	0
		#1 Fired to 33	50	1.20	1.20
		cone. #2	100	4.06	4.01
		electrically	150	7.00	7.00
		fused and	200	10.05	10.50
		fired to 33	250	14.40	14.20
		cone.	300	18.20	18.00
			350	22.20	22.00
			400	26.60	26.40
			450	30.70	30.60
			500	35.10	35.00
			550	39.70	39.40
			600	44.50	44.10
			650	49.20	48.70
			700	54.20	54.50
			750	59.50	59.90
			800	65.00	63.70
			850	70.80	69.20
			900	75.70	75.00
			950	80.60	80.05
			1000	86.60	86.06

Item No.	Trade Designation	% Main Constituent	Temp. °C	Inch/Inch X10^{-4}
222	Unknown	—	25	0
		Electrically	50	1.25
		fused fired	100	4.05
		to 33 cone	150	7.18
			200	15.00
			250	14.40
			350	22.70
			400	27.20
			425	29.40

PYROCERAM

Item No.	Trade Designation	% Main Constituent	Temp. °C	Thermal Expansion Inch/Inch °C X10^{-6}
223	Corning 9606	—	25	2.000
			100	7.500
			125	7.800
			200	4.750
			250	3.655
			300	3.650
			400	3.855
			600	4.153
			800	4.500
			1000	4.850
			1100	5.000

SILICA

224	Corning 7900	—	100	.77
			200	.75
			300	.73
			400	.71
			500	.70
			600	.70
			700	.66
			800	.58
			850	.53

EMISSIVITY
ALUMINA

Item No.	Trade Designation	% Main Constituent	Temp. °C	Emissivity Total Normal		Emissivity Spectral
225	Coors AD995	99.5	100	.82		
			400	.74		
			700	.65		
				Run #1	Run #2	
226	Coors AD995	99.5	100	.77	.78	
			400	.59	.65	
			700	.57	.55	
			900	.45	.49	
			1100	.42	.45	
			1300	.39	.42	
			1375	--	.40	
227	Coors AD995	99.5	24	.780		
			260	.740		
			538	.650		
			816	.545		
			1093	.455		
			1371	.382		
228	Interpace	99.5	100	.78		
			400	.75		
			700	.61		
			900	.54		
			1100	.46		
				Run #1	Run #2	
229	Interpace	99.5	100	.77	.78	
			400	.61	.63	
			700	.53	.51	
			900	.45	.47	
			1100	--	.41	
230	Norton	99.5	100	.79		
			400	.76		
			700	.65		
			900	.57		
			1100	.52		
				Run #1	Run #2	
231	Norton	99.5	25	.78	.75	
			300	.65	.64	

Item No.	Trade Designation	% Main Constituent	Temp. °C	Emissivity Total Normal Run #1	Emissivity Total Normal Run #2	Emissivity Spectral
231			600	.55	.58	
			800	.49	.54	
			1000	.44	.48	
			1300	.42	--	
			1375	.39	--	
232	Norton (LA603)	--	-184	.74		
			149	.74		
			316	.72		
			482	.675		
			649	.63		
			816	.58		.22
			871	--		.24
			982	.53		.29
			1093	--		.34
			1149	.48		--
			1204	--		.39
			1316	.45		.44
			1427	--		.48
			1482	.43		--
			1538			.53
233	Norton (RA-4213)	--	-184	.76		
			149	.77		
			316	.70		
			482	.71		
			649	.52		
			816	.45		
			871	.45		.28
			982	--		.28
			1093	.40		.30
			1149	.36		--
			1204	--		.32
			1316	.33		.35
			1427	--		.39
			1482	.33		--
			1538	--		.44
234	Norton (ROKIDE on stainless steel 446)		-184	.82		
			149	.80		
			316	.77		
			482	.73		
			649	.68		
			816	.62		
			871	--		.44
			982	.57		.45
			1093	--		.48
			1149	.53		--
			1204	--		.51
			1316	.49		--

EMISSIVITY
BERYLLIA

Item No.	Trade Designation	% Main Constituent	Temp. °C	Emissivity Spectral
235	Unknown	--	927	.542
		Hot pressed,	977	.542
		high fired	1027	.543
		BeO.	1077	.544
		Type 1 in	1127	.546
		reference	1177	.549
			1227	.552
			1277	.556
			1327	.559
			1377	.564
			1427	.568
			1477	.572
			1527	.577
			1577	.582
			1627	.587
236	Brush Beryllium	--	927	.212
		Hot pressed,	977	.210
		BeO.	1027	.209
		Type 2 in	1077	.210
		reference	1127	.210
			1177	.211
			1227	.213
			1277	.215
			1327	.217
			1377	.220
			1427	.222
			1477	.225
			1527	.228
			1577	.232
			1627	.235
237	Unknown	--	927	.665
		Hot pressed,	977	.685
		high fired	1027	.706
		BeO.	1077	.727
		Type 1 in	1127	.746
		reference	1177	.766
			1227	.785
			1277	.804
			1327	.819
			1377	.823
			1427	.843
			1477	.854
			1527	.867

Item No.	Trade Designation	% Main Constituent	Temp. °C	Emissivity Spectral
237			1577	.879
			1627	.894
			1677	.911
			1727	.931
238	Brush Beryllium S.P.	--	927	.351
		Hot pressed	977	.371
		BeO.	1027	.383
		Type 2 in	1077	.394
		reference	1127	.405
			1177	.415
			1227	.425
			1277	.435
			1327	.447
			1377	.461
			1427	.474
			1477	.489
			1527	.499
			1577	.507
			1627	.513
			1677	.516
			1727	.517
			1777	.517
			1827	.514
			1877	.509
239	Brush Beryllium	--	927	.336
		Hot pressed,	977	.348
		annealed BeO.	1027	.361
		Type 3 in	1077	.376
		reference	1127	.392
			1177	.407
			1227	.420
			1277	.430
			1327	.439
			1377	.447
			1427	.453
			1477	.459
			1527	.463
			1577	.467
			1627	.470
			1677	.473
			1727	.474
			1777	.475
			1827	.475
			1877	.475

EMISSIVITY
SILICA

Item No.	Trade Designation	% Main Constituent	Temp. °C	Emissivity Total Normal 3/16"	1/4"	5/16"	1/2"
240	Corning 7900	--	149	.87	--	.87	.87
			316	.86	--	.87	.88
			482	.84	--	.86	.88
			649	.82	--	.84	.87
			816	.80	--	.83	.87
241	Corning 7940	--	200	--	.83	--	.84
			300	--	.79	--	.81
			400	--	.75	--	.78
			500	--	.69	--	.74
			600	--	.62	--	.67
			700	--	.55	--	.62

EMISSIVITY
SILICA

Item No.	Trade Designation	% Main Constituent	Temp. °C	Emissivity Total Normal
242	--	--	1300	.60
		Slip Cast	1400	.65
		2-½" l x	1500	.68
		3/4" D	1600	.76
			1700	.70
			1800	.66
			1900	.46
			2000	.38
			2100	.38
			2200	.38
			2300	.38
			2400	.37
			2500	.31
			2600	.23

EMISSIVITY
PYROCERAM

Item No.	Trade Designation	% Main Constituent	Temp. °C	Emissivity Total Normal	Emissivity Normal Spectral
243	Corning 9606	--	149	.84	--
			316	.81	--
			482	.74	--
			649	.69	--
			816	.67	--
			871	--	.40
			982	.63	.44
			1093	--	.48
			1149	.60	--
			1204	--	.52
			1316	.58	.56
244	Corning 9608	--	149	.85	--
			316	.85	--
			482	.85	--
			649	.85	--
			816	.83	--
			871	--	.47
			982	.75	.48
			1093	--	.48
			1149	.64	--
			1204	--	.49
			1316	--	.50

THERMAL DIFFUSIVITY

SILICA

Item No.	Trade Designation	% Main Constituent	Temp. °C	Thermal Diffusivity Cm^2/sec
245	Corning 7940	--	100	.0079
			200	.0078
			300	.0078
			400	.0078
			500	.0079
			600	.0080
			700	.0084
			800	.0088
246	Corning 7941	--	25	.0067
			100	.0060
			200	.0056
			300	.0053
			400	.0051
			500	.0050
			600	.00495
			700	.00490
			800	.00490
			900	.00485
			1000	.00485
			1100	.00485
247	--	--	100	.0033
		slip cast	200	.0032
			300	.0031
			400	.0031
			500	.0032
			600	.0032
248	--	--	100	.0021
		clear, foamed	200	.0019
			300	.0017
			400	.0018
			500	.0020
			600	.0021
			700	.0024

THERMAL DIFFUSIVITY

PYROCERAM

Item No.	Trade Designation	% Main Constituent	Temp °C	Thermal Diffusivity Cm^2/sec
249	Corning 9606	--	25	.0189
			100	.0158
			200	.0140
			300	.0129
			400	.0120
			500	.0112
			600	.0104
			700	.0102
			800	.0099
			900	.0095
250	Corning 9608	--	25	.01190
			100	.00995
			200	.00925
			300	.00870
			400	.00850
			500	.00815
			600	.00875
			700	.00760
			800	.00725

COMPRESSIVE STRENGTH
ALUMINA

Item No.	Trade Designation	% Major Constituent	Temp. °C	Compressive Strength psi x 10^3
251	Coors AD 99.5	99.5	Ambient	> 350
252	Coors AD 99	99.0	Ambient	> 300
253	Coors AD 96	96.0	Ambient	> 300
254	Coors AD 94	94.0	Ambient	> 300
255	Coors AD 85	85.0	Ambient	> 240
256	Wesgo AL 1009	99.85	Ambient	> 100
257	Wesgo AL 995	99.5	Ambient	
258	Wesgo AL 300	97.6	Ambient	
259	Wesgo AL 400	95.0	Ambient	

TENSILE STRENGTH
ALUMINA

Item No.	Trade Designation	% Main Constituent	Temp. °F	Tensile Strength psi x 10^3
260	Coors AD 995	99.5	77	20.82
			500	31.00
			1000	29.24
			1500	-
			1750	-
			2000	8.48
			2250	3.64
			2400	-
			2500	.61
261	Coors AD 99	99.0	70	34 to 35
			2000	21 to 22
262	Coors AD 99	99.0	75	32.0
			500	31.6
			1000	29.5
			1500	24.5
			2000	14.5
			2500	11.2
263	Coors AD 96	96.0	70	26 to 28
			2000	13 to 14
264	Coors AD 94	94.0	70	25 to 27
			2000	9 to 10
265	Coors AD 85	85.0	70	17 to 18
			2000	8 to 9
266	Interpace	99.5	77	18.68
			500	19.60
			1000	20.27
			1500	20.59
			1750	
			2000	15.81
			2250	6.20
			2400	
			2500	2.47

Item No.	Trade Designation	% Main Constituent	Temp. °F	Tensile Strength psi x 10^3
267	Norton	99.5	77	18.98
			500	16.90
			1000	15.19
			1500	15.68
			1750	
			2000	10.52
			2250	2.88
			2500	.60

FLEXURAL STRENGTH
ALUMINA

Item No.	Trade Designation	% Main Constituent	Temp °F	Flexural Strength psi x 10^3
268	Coors AD 995	99.5	77	34.00
			500	39.40
			1000	37.90
			1500	11.60
			1750	
			2000	23.30
			2250	8.00
			2400	
			2500	4.20
269	Coors AD 995	99.5	77	36.3
			500	32.9
			1000	34.7
			1500	36.7
			1750	
			2000	28.9
			2250	19.9
			2500	15.3
270	Coors AD 995	99.5	70	43 to 55
			2000	26 to 31
271	Coors AD 99	99.0	70	47 to 60
			2000	23 to 28

Item No.	Trade Designation	Constituent	Temp °F	Flexural Strength psi x 10^3
272	Coors AD 99	99.0 .050"x.100" Samples. Single Loading 5/8" Span-Loaded at a rate of 30 to 40 pounds per minute	75	53.0
			500	53.5
			1000	53.0
			1500	46.0
			2000	23.5
			2500	10.0
273	Coors AD 96		70	47 to 52
			2000	21 to 26
274	Coors AD 94		70	45 to 50
			2000	15 to 20
275	Coors AD 85		70	40 to 45
			2000	10 to 15

Item No.	Trade Designation	% Main Constituent	Temp °F	Flexural Strength psi x 10^3
276	Interpace	99.5	77	30.90
			500	29.70
			1000	29.70
			1500	28.20
			1750	
			2000	20.90
			2250	12.50
			2400	
			2500	8.20
277	Interpace	99.5	77	38.5
			500	41.1
			1000	40.7
			1500	39.2
			1750	
			2000	17.2
			2250	15.2
			2500	6.9
278	Norton	99.5	77	27.80
			500	28.70
			1000	28.50
			1500	14.60
			1750	20.80
			2000	
			2250	10.10
			2500	3.10
279	Norton	99.5	77	28.2
			500	27.3
			1000	27.5
			1500	28.3
			1750	
			2000	18.0
			2250	5.8
			2500	2.5
280	Wesgo AL1009	99.85	Ambient	23
281	Wesgo AL995	99.5	Ambient	62
282	Wesgo AL300	97.6	Ambient	46
283	Wesgo AL400	95.0	Ambient	64

YOUNG'S MODULUS-SHEAR MODULUS-POISSON'S RATIO
ALUMINA

Item No.	Trade Designation	% Main Constituent	Temp °F	Young's Modulus psi x 10^6	Shear Modulus psi x 10^6	Poisson's Ratio
284	Coors AD995	99.5	77	52.6	21.2	.243
			500	50.4	20.6	.227
			1000	49.5	20.2	.239
			1500	47.2	18.6	.235
			1750	46.3	17.4	.283
			2000	44.9	17.2	.306
			2250	40.2	16.3	.289
			2400	35.5	15.3	.225
			2500	34.5	15.2	.216
285	Coors AD995	99.5	77	52.8	20.6	.28
			500	51.2	20.0	.28
			1000	49.5	19.3	.28
			1500	47.4	18.4	.29
			1750	46.3	18.0	.29
			2000	45.1	17.6	.28
			2250	42.3	17.2	.25
			2500	42.5	18.6	.14
286	Coors AD995	99.5	75	52.5	20.7	
			500	52.0	20.5	
			1000	50.7	19.7	
			1500	48.3	18.9	
			2000	45.7	17.7	
			2500	41.5	15.9	
287	Coors AD995	99.5	Ambient	50.00	-	-
288	Coors AD99	99	75	50.9	21.5	.205
			500	50.7	21.2	.200
			1000	49.7	20.9	.189
			1500	47.9	20.0	.198
			2000	45.0	17.6	.279
			2500	38.0	13.5	.410
290	Coors AD99	99	70	50.0		
291	Coors AD96	96	70	47.0		
292	Coors AD94	94	70	40.2		
293	Coors AD85	85	70	31.9		

Item No.	Trade Designation	% Main Constituent	Temp °F	Young's Modulus psi x 10^6	Shear Modulus psi x 10^6	Poisson's Ratio
294	Interpace	99.5	77	51.9	21.0	.234
			500	51.5	19.9	.281
			1000	49.3	19.4	.280
			1500	48.7	18.5	.305
			1750	46.5	18.0	.295
			2000	42.5		.265
			2250	40.2		.191
			2400	-		
			2500	38.4		
295	Interpace	99.5	77	47.0	20.4	.15
			500	47.7	19.8	.21
			1000	46.4	19.1	.21
			1500	43.8	18.3	.20
			1750	43.5	18.0	.21
			2000	42.3	16.6	.27
			2250	40.9	16.4	.25
			2500	-	-	-
296	Norton	99.5	77	48.5	19.0	.240
			500	47.0	18.8	.223
			1000	45.5	17.4	.276
			1500	44.0	16.6	.275
			1750	42.8	16.5	.251
			2000	41.4	10.4	.324
			2250	35.7	13.8	.270
			2500	30.4	9.9	.424
297	Norton	99.5	77	44.9	17.9	.25
			500	44.2	17.5	.26
			1000	43.1	16.8	.28
			1500	41.2	16.1	.28
			1750	39.9	15.1	.31
			2000	39.4	14.8	.33
			2250			
			2500			

TENSILE STRENGTH-COMPRESSIVE STRENGTH-FLEXURAL STRENGTH-YOUNG'S MODULUS
BERYLLIA

Item No.	Trade Designation	% Main Constituent	Temp °F	Tensile Strength psi x 10^3	Compressive Strength psi x10^3	Flexural Strength psi x10^6	Young's Modulus psi x10^6
298	Coors	100.0	75	16.8			
			500	16.4			
			1000	14.5			
			1500	12.8			
			2000	8.5			
			2500	1.2			
299	Coors BD-96	96.0	72		> 225	32.10	46
			500			31.00	
			1000			35.20	
			1500			34.50	
			2000			9.12	
300	Coors BD-98	98.0	72		> 225	36.4	46
			500			32.4	
			1000			36.1	
			1500			39.7	
			2000			13.0	
301	-	-	78	18.5-13.8	300-140		
			932	11.1	71.0		
			1472		64.0		
			1652	7.0			
			1832		35.5		
			2086	2.0			
			2092		28.5		
			2372	.6			
			2552		24.0		
			2732		17.0		
			2912		7.0		

TENSILE STRENGTH-FLEXURAL STRENGTH-YOUNG'S MODULUS-SHEAR MODULUS-POISSON'S RATIO
PYROCERAM

Item No.	Trade Designation	Temp °F	Tensile Strength psi x 10^3	Flexural Strength psi x 10^3	Young's Modulus psi x 10^6	Shear Modulus psi x 10^6	Poisson's Ratio
302	Corning	78		38.25	17.20	6.90	.2430
	Pyroceram	200		38.20	16.82	6.80	.2430
	9606	302		37.75	16.70	6.70	.2430
		400		37.25	17.40	6.93	.2506
		500		36.50	17.62	7.08	.2500
		1000		30.50	17.80	7.17	.2438
		1300		24.75	17.60	7.14	.2398
		1500		19.00	17.50	7.08	.2370
		1750		11.25		6.98	
		2000		7.25			
		2500		6.50			
303	Corning	78	22.3	19.6*			
	Pyroceram	500	18.2	19.6			
	9606	1000	17.6	22.6 25.7**			
	*Round Sample	1500	9.5	18.4 24.2			
		1750	9.3	11.7 24.1			
	**Rectang-	2000	5.5	6.5 17.8			
	ular Sample	2250	2.7	5.4			
304	Corning	78	22.5	32.2++		6.16+	.224
	Pyroceram	257			16.0	6.08	.200
	9606	302			16.01		
	(Fortified)	347				6.09	.227
	+2.84gm/cc	500	25.6	36.1		6.26	.198
		1000	26.6	32.2		6.33	.219
	++Round	1200			17.0		
	Sample	1350			16.9		
		1500	6.3	12.9	16.8	6.15	.190
		1750	6.4	9.4	16.0	5.33	.237
		2000	4.8	7.6	14.1	5.32	.140
		2250	3.3	7.5	10.2	4.43	.136

TENSILE STRENGTH-YOUNG'S MODULUS-SHEAR MODULUS
MAGNESIA

Item No.	Trade Designation	% Main Constituent	Temp °F	Tensile Strength psi x 10^3	Young's Modulus psi x10^6	Shear Modulus psi x 10^6
305	-	-	Ambient	14.0	30.5	16.7
			392	14.0	30.5	
			752	15.2	30.0	
			932			23.0
			1112		29.5	
			1472	16.0	27.5	
			1832	11.5	21.0	10.3
			2012	10.0		8.4
			2192	3.0	10.0	7.7
			2372	6.0	4.0	5.2

TENSILE STRENGTH-COMPRESSIVE STRENGTH-YOUNG'S MODULUS-SHEAR MODULUS
SPINEL ($MgO:Al_2O_3$)

Item No.	Trade Designation	% Main Constituent	Temp °F	Tensile Strength psi x10^3	Compressive Strength psi x 10^3	Young's Modulus psix10^6	Shear Modulus psi x10^6
306	-	$MgO:Al_2O_3$	Ambient	19.0	270.0	34.5	13.2
			392			34.4	13.1
			752			34.3	12.8
			932		199.0		
			1022	13.7			
			1112			34.0	12.4
			1472		171.0	32.9	11.6
			1652	10.8			
			1832			30.4	10.3
			2012		85.5		
			2122	6.1			
			2192		71.0	25.0	8.5
			2372	1.1		20.1	7.2
			2552		21.4		
			2912		8.5		

FLEXURAL STRENGTH-YOUNG'S MODULUS-SHEAR MODULUS-POISSON'S RATIO
FUSED SILICA

Item No.	Trade Designation	% Main Constituent	Temp °F	Flexural Strength psi x10^3	Young's Modulus psi x 10^6	Shear Modulus psi x10^6	Poisson's Ratio
307	Corning		78	14.30* 6.50			.1535
	Fused Silica		200	14.50 6.60	8.70	3.73	.1565
	7941		302	14.60 6.75	8.94	3.83	.1585
			400	14.75 6.90	9.16	3.86	.1600
	*Strengthened		500	14.80 7.00	9.37	4.01	.1620
	by Special		1000	15.50 7.75	10.11	4.43	.1710
	Techniques;		1300	16.00 8.25	10.19	4.55	.1765
	Single point		1500	16.30 8.75	9.90	4.55	.1820
	loading 3 1/2"		1750	16.90 9.25			
	span .437"		2000	17.50 9.75			
	diameter						
	20,000psi load						
	rate						